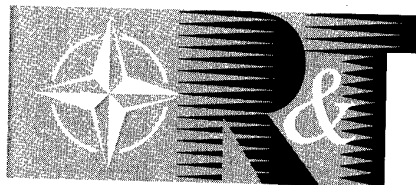


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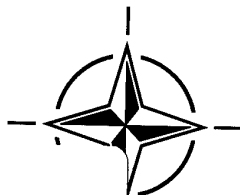
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RTO TECHNICAL REPORT 4

Cervical Spinal Injury from Repeated Exposures to Sustained Acceleration

(Les traumatismes de la colonne cervicale dus aux accélérations soutenues et répétitives)

A report prepared by the Human Factors and Medicine Panel (HMF) on the results of a Technology Watch established by the former AGARD Aerospace Medicine Panel (AMP).



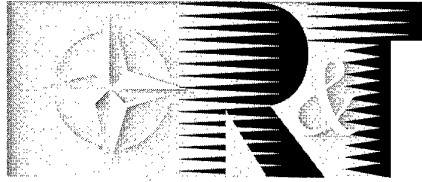
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**Cervical Spinal Injury from Repeated Exposures
to Sustained Acceleration**

(Les traumatismes de la colonne cervicale dus aux accélérations soutenues et répétitives)

by

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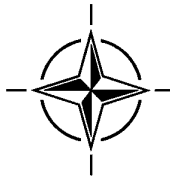
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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

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Cervical Spinal Injury from Repeated Exposures to Sustained Acceleration

(RTO TR-4)

Executive Summary

The Aerospace Medical Panel of the former Advisory Group for Aerospace Research and Development (AGARD) established Working Group (WG) 17 on 'The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G' that resulted in Advisory Report (AGARD-AR-317). That WG developed substantial evidence that aircrew of high-performance aircraft suffered various types of spinal injury from exposures to sustained G; however, their findings were not compelling. Therefore the WG recommended the establishment of a Technology Watch on that topic to review current research data and published articles. Dr. Russell R. Burton chaired this TW that was established in 1995. This Technical Report (TR) is the final report of that TW.

This TW noted a very high rate of acute injury to soft tissues (muscles and ligaments) of the neck in fighter pilots that was a result of sustained G exposures. It also reported that in several pilot high-sustained G studies there were significantly greater incidences of degeneration of the cervical spine compared with low or no G exposed, age-sex matched controls. These data were obtained from ongoing cross-sectional and longitudinal studies and published reports. Meta-analysis of 8 studies determined that there was a direct relationship between degenerative diseases of the spine and repeated exposures to sustained G. The statistical probability of this analysis was $P < 0.001$.

The following hypothesis was developed. Acute injuries of neck muscles and ligaments commonly occur in fighter pilots. These injured soft tissues of the neck are less able to protect the cervical spine from reoccurring increased G generated external loads. Thus subacute disk injuries occur that eventually lead to spinal degeneration and the development of osteophytes with vertebral strengthening. This G-effect on the spine appears to be an acceleration of spinal degeneration that normally occurs with increasing age in low or non-G controls. Thus it is hypothesized that both populations will eventually have similar levels of cervical spinal degeneration after pilots are no longer exposed to sustained G.

Recommendations included:

- That more research should be conducted on this topic, particularly in older subjects.
- That a symposium on this topic should be conducted by RTA in approximately 10 years.
- That nomenclature on acute and chronic injuries should be standardized.
- That an international database on cervical injuries related to sustained G should be established.
- Specific considerations on the prevention and treatment of acute neck injuries.

Les traumatismes de la colonne cervicale dus aux accélérations soutenues et répétitives

(RTO TR-4)

Synthèse

Le Panel de médecine aérospatiale de l'ancien Groupe consultatif pour la recherche et les réalisations aérospatiales (AGARD), a créé le groupe de travail No. 17 sur «Les effets musculosquelettiques et vestibulaires des fortes accélérations soutenues et répétitives», qui a édité le rapport consultatif AGARD-AR-317. Ce groupe de travail a réuni des preuves probantes attestant que les équipages des avions à hautes performances souffraient de différents types de traumatismes de la colonne vertébrale à cause des accélérations soutenues. Cependant, leurs conclusions n'ont pas été jugées convaincantes. Par conséquent, le groupe de travail a recommandé l'instauration d'une veille technologique sur ce sujet afin de faire le point des résultats des recherches en cours et des articles publiés. Cette activité de veille technologique, qui a démarré en 1995, a été présidée par le Dr Russell R. Burton. Ce rapport technique (TR) est le dernier rapport de ce groupe.

Le rapport a fait état d'un niveau important de traumatismes aigus des tissus mous du cou chez les pilotes de chasse résultant des fortes accélérations soutenues. Il a indiqué aussi que plusieurs études sur les fortes accélérations soutenues faisaient apparaître des signes de dégradation de la colonne cervicale sensiblement plus importants que ceux relevés sur des sujets témoins d'âge et de sexe identiques, n'ayant pas subi de facteurs de charges ou bien à de faibles niveaux. Ces données ont été obtenues à partir d'études et d'échantillons de population, ainsi que des différents rapports publiés. Une méta-analyse des 8 études a trouvé une relation directe entre les maladies dégénératives de la colonne dorsale et l'exposition répétée aux fortes accélérations soutenues, la probabilité statistique de cette analyse étant de $P < 0.001$.

L'hypothèse suivante a été avancée : Les lésions graves des muscles et ligaments du cou se produisent souvent chez les pilotes de chasse. Ces tissus mous du cou endommagés ne peuvent plus assurer la même protection de la colonne cervicale contre des charges externes accrues résultant des forces d'accélération. Ainsi, se produisent des lésions subaiguës qui ont pour effet, à terme, la dégradation de la colonne vertébrale, accompagnée du développement d'ostéophytes, avec renforcement vertébral. L'effet de ces forces d'accélération sur la colonne vertébrale semble être une dégradation accrue de la colonne vertébrale qui se produit normalement à un âge plus avancé chez les sujets exposés ou non à des faibles facteurs de charge. L'hypothèse est donc avancée que les deux populations afficheront des degrés de dégradation cervicale similaires une fois que les pilotes ne subiront plus de fortes accélérations soutenues.

Le groupe a fait les recommandations suivantes :

- plus d'efforts de recherche devraient être consacrés à ce sujet, en particulier chez les sujets d'un âge plus avancé.
- un symposium sur ce sujet devrait être organisé par la RTA dans 10 ans environ.
- une nomenclature normalisée des lésions aiguës et chroniques devrait être établie.
- une base de données internationale sur les lésions cervicales dues aux fortes accélérations soutenues devrait être établie.
- des considérations spécifiques sur la prévention et le traitement des lésions aiguës du cou ont été signalées.

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Preface

The Aerospace Medical Panel (AMP) of the former Advisory Group for Aerospace Research and Development (AGARD) expressed concern in 1970 about the possibility of a causal relationship between spinal disorders and aerobatics with publication, AGARDOGRAPH 140, 'Physiopathology and Pathology of Affections of the Spine in Aerospace Medicine' (22). It was reported that cervical arthrosis had a higher incidence in pilots above 30 years of age. 'Air experience' was considered as the likely cause of this increased incidence of cervical arthrosis in older pilots.

In 1982, another AGARDOGRAPH was published on this subject entitled 'Physiopathology and Pathology of Spinal Injuries' (AGARD-AG-250). This publication made several references to reports of spinal injuries associated with high-G exposure and concluded that high-sustained-G capabilities of modern fighter aircraft will make spinal disk arthritis the '... future disease of combat pilots' (23).

In 1985, the former AGARD published yet another Conference Proceedings AGARD-CP-378 on a similar topic, 'Backache and Back Discomfort' that resulted from an AMP Symposium presented on 7-11 Oct 1985, Naples IT (30; 104). In that publication it was noted that fighter pilots with and without lower back pain had narrowing of the spinal disk spaces that prompted the authors to conclude 'disc degeneration may be accelerated by repeated Gz forces experienced by pilots of fighter aircraft'.

Once again in 1989, 24-28 April, another symposium on a related topic entitled 'Neck Injury in Advanced Military Aircraft Environments' was conducted that resulted in Conference Proceedings AGARD-CP-471 of the same title (30). As recommended by the 1989 Proceedings, AGARD Working Group 17 (WG 17) was established that resulted in AGARD/AMP Advisory Report 317 'The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G' (AGARD-AR-317) in May 1994 (3).

Advisory Report 317 recommended that the AMP establish a Technology Watch (TW) group on Spinal Injury from Repeated Exposures to High-Sustained Acceleration. This advisement was the result of information collected and reviewed by WG 17 that provided substantial evidence that aircrew of high-performance aircraft suffered various types of spinal injury from exposures to high-sustained G. Thus a TW was approved by AMP and established by the former AGARD to gather and analyze additional information on this subject and report regularly its findings to AGARD/AMP. The membership of this TW had representatives from most NATO Nations and Japan, Poland, Russia and Sweden. National representatives were usually flight surgeons closely aligned with the operational community of aircrew flying high-performance aircraft. Members of the TW compiled information on the subject of spinal injury from their countries of published articles, technical reports, and anecdotal information. This information was compiled, analyzed and summarized by the TW Chairperson, Dr. Russell R. Burton, US. Semi-annual reports were orally presented informally by the TW Membership or their representatives at regular AMP Business Meetings. Information from these reports provided the core of this TR. That information was combined and analyzed in detail using appropriate knowledge bases and specialists expert on the topics of spinal injury and degeneration. Hence this TR provides **value added** resulting in a knowledge base far greater than the sum of the information provided by all of the individual reports.

With the reorganization of research and technology activities in NATO, this effort that started under the auspices of the former AGARD is now under the direction of the Research and Technology Organization (RTO). A final report of the information obtained and developed by this TW was recommended to AGARD/RTO to be published as a Technical Report (TR). That recommendation was approved and funds for that publication were made available by RTO.

The appointed member of the TW from each nation was: Belgium, P. Van Strydonck; Canada, H. O'Neill; Denmark, S. Lydich; France, A. Trouset; Germany, H. Pongratz; Greece, I. Diamatopoulos; Japan, S. Tachibana; Netherlands, W. Tielemans; Norway, O. Kielland; Poland, A. Stepień; Portugal, N. Ribeiro; Russia, G. Stupakov; Spain, F. Tejada; Sweden, J. Linder; Turkey, M. Savasan; U. K., N. Green; U. S., R. Vanderbeek; and R. Burton (Chairperson).

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GLOSSARY OF TERMS AND ACRONYMS

ACM = Aerial Combat Maneuver (ing) – changes in aircraft positions when two fighter aircraft engage each other in combat. Rapid turns develop accelerations of varying levels on the aircraft and aircrew. This maneuver of various G levels is continuous that can last for several minutes.

AGARD = Advisory Group for Aerospace Research and Development – Research body of NATO. Formed after World War II it was reorganized in 1997 into the RTO.

AGARDograph = AGARD Publication of a comprehensive review on a specific topic.

AGSM = Anti-G Straining Maneuver – maximum muscle contraction of all major muscles of the body in combination with a forced expiration against a closed or partially closed glottis that increases eye-level arterial blood pressure. Sometimes referred to as an M-1 or L-1 maneuver. Used by fighter pilots to increase their G tolerance during ACM.

AMP = Aerospace Medical Panel – group of scientists, engineers, and physicians in AGARD that addressed medical, performance, and life- support research and development issues of aircrew.

AR = Advisory Report – publication arising from a WG. (See TR).

AROM = Active Range of Motion – degrees of maximum voluntary movement of body joints.

Arthrosis = degenerative disease of joints; i.e. arthritis.

Arthrosis deformans = type of arthrosis.

BMI = Body Mass Index – body weight (mass in kg)/ squared body height (m^2).

CAT or CT = Computer Axial Tomography – imaging technique that does not expose the body to radiation. See X-ray.

CBL = Compression Breaking Load – external load applied slowly (in Newtons, N) that will fracture a vertebra.

Cervical = refers to section of spine that is composed of 7 vertebrae designated by vertebrae numbers; i.e. C₁ – C₇.

Check six = position of the head of the pilot that is rotated and perhaps flexed or extended in order to see aircraft that are behind them.

Degeneration = abnormal changes of the spine that usually involves disks and vertebrae. Disks narrow and may protrude or herniate into the spinal canal. Vertebrae develop osteophytes forming a condition known as spondylosis.

Disk or Disc = elastic-fibrous body that separates vertebrae; i.e., intervertebral disk or disc. The 'disk' spelling is used in this text. Location is designated in relationship to the vertebrae; e.g., C₅ – C₆ or C₅₋₆ disk.

Dystrophy (ic) = weakening or degeneration; i.e., atrophy.

EMG = Electromyography – method used to measure level of muscle activity.

Eurofighter = advanced European fighter aircraft capable of 9 G in 1 s that was designed by several European countries.

F-1, F-27 = low performance aircraft used primarily for training fighter pilots. Usually operates at < 4 G.

F-15, F-16 = operational high performance fighter aircraft that are capable of generating 9 G within one s. Produced in the US for the US Air Force it is used by several foreign nations.

F-18 = operational high performance fighter aircraft that is capable of generating 7.5 G within one s. Produced in the US for the US Navy it is used by several foreign nations.

F-22 = advanced US Air Force fighter aircraft, capable of 9 G in 1 s.

French Rafale = operational high performance French fighter aircraft that is capable of generating 9 G within one s.

G = inertial force, expressed as multiplies of Earth's gravity (1 G), opposed to an equal acceleration force (g). Type of G that fighter pilots are exposed to during an ACM. Used herein it always denotes positive G (+G_z) – head to foot directed inertial force.

Gripen = advanced Swedish fighter aircraft capable of 9 G in 1 s.

Herniation of a disk = an intervertebral disk protruding into the spinal canal.

HPA = High Performance Aircraft – fighter aircraft capable of generating high sustained G.

HSG = High Sustained G - human exposure ≥ 6 G for longer than 15 s.

HUD = Head Up Display – primary cockpit instruments are displayed at pilot eye-level appearing to be on the windscreen.

IEMG = Inflight EMG – technique used to measure an EMG on aircrew during flight or Integrated EMG – EMG signal is rectified to enable amplitude calculations.

Intervertebral = between vertebrae. Usually refers to the intervertebral disk. See disk.

MiG and Su = Russian built high-performance fighter aircraft with number designations. Higher numbered aircraft are capable of generating 9 G within one s.

Moment = used in engineering that denotes the physical relationship of a mass (force) to its perpendicular distance from an axis.

MRI = Magnetic Resonance Imaging – imaging technique that does not expose the body to radiation. See X-ray.

MUR = Muscular Utilization Ratio – muscle moment of force required/ Maximum muscle strength.

MVC = Maximum Voluntary Contraction – measure of a muscle contraction (%) related to its maximum capability of 100%. The EMG during different work conditions can be normalized to activity during isometric MVC and thus be expressed as % MVC. MVC > 100% indicates muscle strain.

MVF = Maximum Voluntary Force – maximum force (Newtons, N) that a muscle can exert with a MVC.

Myelogram = image of the spinal cord.

NATO = North Atlantic Treaty Organization – organization of nations of Western Europe aimed at mutual defense.

O'clock position = orientation of the head of the pilot as related to the hands of a clock. 12 O'clock is head in the forward position and 5 or 6 O'clock is facing the rear of the aircraft.

Osteophytes = bony growths of vertebrae. Tend to protrude and grow over intervertebral disks fusing the spine.

Osteophytosis = formation of osteophytes.

Radiographs = X-rays.

Spondylosis = condition of the spine exhibiting osteophytes.

RTA = Research and Technology Agency is the functioning research body within RTO.

RTO = Research and Technology Organization formed from AGARD in 1997.

Stenosis = narrowing of a canal or opening.

TR = Technology Report – publication format of RTO used for technology reviews.

TW = Technology Watch – continuously obtaining current information on a specific topic.

UCS = Ultimate compression strength – ability of a vertebra to resist weight (breaking) expressed as kg/mm².

WG = Working Group – an operational body (designated by AGARD) composed of a relatively small group of research specialists that met regularly (semi-annually) for a limited time (usually 2 years) on issues regarding a specific topic. The final report of a WG (designated by a number) was usually a publication such as an AR or TR.

X-ray = imaging technique that uses X-rays, thus exposing the body to radiation.

CHAPTER 1

INTRODUCTION

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1.1 TECHNICAL REPORT (TR) FOCUS AND ORGANIZATION

This Technical Report (TR) is the final report of the 'Technology Watch on Spinal Injury from Repeated Exposures to Sustained Acceleration'. This TR aims to provide an increased understanding of the effects of repeated exposures to sustained acceleration (G) on acute neck injury and degenerative changes of the cervical spine. However the term 'repeated exposures' in the title perhaps incorrectly suggests that we are considering only cumulative effects. Single exposures to sustained G can result in acute injuries that appear to relate to cumulative/degenerative effects. Therefore acute injuries are considered in this TR as they relate to degenerative changes.

Also this Technology Watch (TW) group which began considering the entire spine, soon realized that the cervical spine was at greatest risk. In the increased sustained G environment we found that the cervical spine suffers the vast majority of acute injuries and chronic changes. Therefore this TR is primarily concerned with acute injuries and degenerative changes of the cervical spine and related anatomical structures. However there is evidence that the lumbar spine suffers some injuries from the flight-environment, but these tend to occur most commonly in helicopter pilots. A future study by the Research and Technology Agency (RTA) in the near future should perhaps address this potential operational problem.

This TR is organized as it relates to the operations of the Technology Watch (TW). Since the main focus of the TW was to obtain information on the topic of spinal injury, a literature review was made of current reports and research articles. Those are listed in this chapter in annotated form. Information from those publications was reviewed, analyzed, organized, and summarized into Chapters 2 and 3.

This TW was fortunate to be active as several studies on this subject were ongoing or had just been completed independently by several nations; i.e., The Netherlands, Spain, Japan, and Sweden. Each of these studies is a separate chapter. Other chapters

include reports from individual nations on previous studies, their experiences and concerns about cervical injuries associated with the sustained-G environment; i.e., Turkey, Russia, Poland and Finland.

Chapter 12 provides basic medical, anatomical and biomechanical information for readers that are not converse on this subject. Perhaps the reader, with limited knowledge on this subject should read this chapter first. Terms and acronyms are defined in a glossary that precede Chapter 1.

Since all studies on this subject have small numbers of participants and are quite diverse in their protocols, meta-analysis calculations were performed to increase the power of those results. The results of that analysis are found in Chapter 13.

The last two chapters provide a summary, conclusions, and recommendations to be used by professionals engaged or interested in this topic. It is suggested that these chapters be read last in order for the serious reader to evaluate these conclusions and recommendations as they consider the information found in Chapters 1 through 13 that provided the bases for Chapters 14 and 15.

1.2 BACKGROUND

High-performance fighter aircraft of many nations are capable of generating high-sustained accelerations that expose aircrew to inertial forces up to 9 G. Because of the upright seat configuration in the cockpit of all fighter aircraft, the pilot is exposed to this acceleration only as $+G_z$ directed inertial forces. Therefore in this TR, the symbol 'G' always represents $+G_z$ (head-to-foot inertial force) unless otherwise stipulated.

Although G-levels $>5G$ are above natural human G tolerances, modern G protective systems that are currently operational in many Air Forces are capable of allowing pilots to routinely perform repeated long-duration G maneuvers up to 9 G. Therefore these aircraft, along with advanced G protective systems, have significantly increased the sustainable G

envelope for aircrew flying high-performance aircraft.

The cumulative anatomic and physiologic effects of these repeated high-sustained G exposures over the life flying time of these aircrew are unknown. Indeed, we assume that if the human can acutely 'tolerate' the physical extremes of the environment, then the exposure did not result in any pathology (17). However in reality, we have increased the so-called 'G tolerance' of aircrew with G-protective equipment that does not protect at all, but only increases the level of the hazard - - uniquely G forces directly affect all of the anatomy and physiology of the body during every G exposure. An anatomic structure of particular concern to the medical community is the spine as it supports the weight of the head and much of the body. During exposures to increased G, the weight (load) is increased by a factor of the G level during sustained-G exposures; i. e., the head of a pilot weighs approximately 150 pounds (68 kg) while he/she is at 9 G.

Concerns about aircrew injury from exposures to high sustained G were documented in the Advisory Group for Aerospace Research and Development (AGARD) Conference Proceedings (AGARD-CP-471) that resulted from an AGARD/Aerospace Medical Panel (AMP) Symposium on 'Neck Injury in Advanced Military Aircraft Environments', April 1989 (10). As recommended in these proceedings, AGARD Working Group 17 (WG 17) on this topic was established that resulted in an AGARD/AMP Advisory Report 317 'The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G' published in May 1994 (3).

Advisory Report 317 recommended that the AMP establish a TW on Spinal Injury from Repeated Exposures to Sustained Acceleration. This advisement was the result of information collected and reviewed by WG 17 on this topic. The evidence for the existence of spinal injury in aircrew of high-performance aircraft was substantial but not compelling. This WG considered recommending a control survey of this topic, either cross-sectional or longitudinal, of aircrew from several nations. In the end, this was not their recommendation because of the many administrative and logistical challenges dealing with different nations and the high-cost factor. Also long-duration requirements of such studies could not be justified or supported by AGARD. Nonetheless, a long-term well-coordinated multinational prospective study using the same research protocol would still be the best approach in defining these spinal problems.

Therefore the TW, recommended by WG 17, was proposed by AMP and was approved by AGARD to

gather and analyze additional information on this subject and report its findings annually to AGARD/AMP. The membership of this TW had representatives from all NATO nations; Sweden, Japan, Poland and Russia. Indeed these non-NATO countries participated voluntarily because they too had concerns about G-induced pathologic spinal problems.

National representatives were generally flight surgeons closely aligned with the operational community of aircrew flying high-performance aircraft. Members of the TW compiled information on spinal injury from their country using published articles, technical reports, and anecdotal information. All of this information was coordinated, reviewed and summarized by the TW chairperson, Dr. Russell R Burton (US) in Chapters 2 and 3. This information was reported at semi-annual meetings of the TW at regular AMP Business Meetings. These reports showed that several nations were conducting research studies on this subject of spinal injury. Consequently progress reports on those studies, were presented at these meetings by the Principal Investigators of the studies or their representatives.

Concerns about an increase in neck pathologies in men and women flying high performance have been heightened with the near-term introduction into operations of advanced designs of fighter aircraft with higher-sustained G capability; i.e., Eurofighter, Gripen, and F-22. The US F-15 and F-16, French Rafale and Russian MiG-29/Su-27 have these capabilities now, including advanced G protective systems that allow pilots to routinely fly at high-G and with only moderate fatigue. Thus more high-G sorties can be sustained over the lifetime of a pilot. Consequently, this means more exposures to sustained high G with increased G-loading on the spine and potentially increasing the environmental health risk of these pilots.

AGARD/AMP was particularly well suited to support this TW for several reasons. First, neck injury is a medical problem that uniquely concerns the AMP and second, neck-injury data as medical information are best developed, obtained and interpreted by medically trained scientists. Finally, this type of activity can only be addressed through a multi-national organization such as NATO/AGARD/ROTO.

The primary value of the TW is that it provided a platform for experts to assemble and discuss data from many studies (from different nations), each of which usually had few subjects. In addition, this TW prompted its membership to review their own nation's databases for relevant information. Indeed, three nations (Spain, Japan and Sweden) conducted prospective research studies on this subject in support

of the interests of the TW. Also, Technical Reports and anecdotal information were obtained by the membership of the TW which were not readily available by other means. Obtaining all of the available information on this topic is essential if a credible attempt is to be made to establish a causal relationship between repeated sustained-G exposures and degenerative pathologies of the spine. This effort becomes particularly difficult relative to the degenerative disease aspects. Degeneration of the spine has rather obscure symptomatology and its onset and progress are directly related to increasing age.

If a causal relationship between sustained G exposure and spinal degeneration is found to exist, what is the value of this information especially since sustained G exposures are inevitable for fighter pilots? There are several reasons to explore such a relationship. Certainly, the knowledge that there is a causal relationship is an important occupational health issue for persons who choose to fly these aircraft - they should be aware of an increased risk. Also in order to reduce the incidence rate of this occupational disease (if one exists), relevant detailed information will be necessary to identify:

- (1) Duration and frequency of G exposures necessary to cause the disease;
- (2) Site(s) of the injury or degenerative change in the spine;
- (3) Exact nature of the disease (precise diagnosis); and,
- (4) Predisposing factors such as age, prior spinal conditions, family histories and life styles.

Knowledge of this information can support:

- (1) Pilot selection processes to include spinal examination of candidate pilots;
- (2) Development of counteractive strategies; e.g. exercise programs; improved seat designs; and, back or neck supports;
- (3) Development of intervention strategies in the disease process with early diagnosis and aggressive treatments; and,
- (4) Fact-based logic in design of head-mounted systems, seats, and aircraft.

1.3 HISTORICAL PROSPECTIVE

Concerns about acute spinal injury from exposure to sustained acceleration during flight have been documented for many decades beginning when aircraft were not capable of routinely sustaining very high G levels. Nonetheless, 9 G exposures were possible if only for a few seconds, in some of these vintage aircraft but usually only under "emergency" situations.

The first documented spinal injury from sustained G exposures was by Shaw (114) in 1948 who reported on two scenarios that involved sustained levels of 5 and 9 G. The latter G exposure was an emergency pull out from a dive that was sustained for 2-3 seconds. Both injuries involved spinal disk ruptures in the lumbar regions. Interestingly at that time, the lumbar spine, not the cervical spine was considered the most likely site for spinal injuries to occur from exposures to sustained G. Consequently, the first experiment to examine the lumbar spine during sustained G exposures used a centrifuge with exposures up to 6 G (20). As time passed and more information became available about spinal injury, interest shifted from the lumbar to the cervical spine suggesting different causal relationships with sustained exposures to higher G levels.

On the other hand, in 1964 Myers (88) who reported on 66 aircrew operated on for spinal diseases, noted that none were related to excessive 'G forces'. This report suggests strongly that repeated sustained 4-5 G did not cause any significant degenerative spinal disease. Recently, Hamalainen et al (35) concluded that acute neck injuries due to sustained exposures required > 4 G (see chapter 10).

AGARD became concerned about the relationship between spinal disorders and aerobatics in 1970 with a publication, AGARDograph 140, 'Physiopathology and Pathology of Affections of the Spine in Aerospace Medicine' (22). It should be noted that during this time aircraft were pulling a maximum of 7 G during aerial maneuvers with most sustained-levels at 5-6 G. Nonetheless, it was reported that a fighter pilot experienced neck pain during an aerobatic sortie. Arthrosis of the C₃-C₄ and C₅-C₆ disks were found. This publication also noted that there was a higher incidence of cervical arthrosis in pilots older than 30 years of age. 'Air experience' was considered the cause of this increased incidence of arthrosis in older pilots. These observations caused some concern even though it is well known that increasing age is directly correlated with increased spinal degeneration.

Approximately a decade later, another AGARDograph was published in 1982 on this subject 'Physiopathology and Pathology of Spinal Injuries' (23). That publication made several references to reports of spinal injuries associated with high-G exposure. 'Acquired spinal disease, especially in older pilots, requires study because its incidence is not decreasing' (page 7 of that report). That publication reports on a 3 year study that showed 60% abnormal curvatures in 120 fighter pilots aged 20-30 compared with 5% age-matched controls without high-G exposure (page 261). That AGARDograph concludes that:

- (1) '... for the moment it is not possible to state with certainty that flight in high speed combat aircraft contributes to the development of cervical arthritis...' (page 263);
- (2) the cervical spine is the most vulnerable in fighter pilots because of high-G exposures; and,
- (3) new high performance aircraft (e.g. Mirage 2000 and F-16), because of their high-sustained-G capabilities will make spinal disk arthritis the 'future disease of combat pilots' (page 294).

In 1985, AGARD published Conference Proceedings AGARD-CP-378 'Backache and Back Discomfort'. In that publication, Froom, et al (30) noted that fighter pilots with and without lower back pain had narrowing of disk spaces that prompted the authors to conclude that 'disc degeneration may be accelerated by repeated G_z forces experienced by pilots of fighter aircraft'.

From this history, beginning shortly after World War II, one can see that the interest in spinal injury of pilots was accelerating. So it was not surprising that AGARD/AMP considered having yet another symposium on this topic in 1989 'Neck Injury in Advanced Military Aircraft Environments' that resulted in AGARD Conference Proceedings, AGARD-CP-471 of the same title (10).

This symposium considered injuries from ejection as well as in-flight exposures to high-sustained G. By far the majority of presentations were on ejection- and impact-related injuries; however, there was considerable information and interest generated at this symposium on in-flight injuries. This information raised concerns that resulted in the formation of AGARD/AMP Working Group 17 on the musculoskeletal and vestibular effects of repeated exposures to sustained high G. A summary of this symposium (10) made three important conclusions regarding exposures to maneuvering G:

- (1) acute injuries commonly occur that involve soft and hard tissues of the neck,
- (2) repetitive exposures probably lead to spinal degenerative changes in the cervical region (e.g., cervical osteophytes and intervertebral disks), and
- (3) a need to include chronic injury in the classification scheme for neck injuries.

The method of classification of neck injuries developed in AGARD-CP-471 that follows, appears to be quite complete and will be generally used to categorize the in-flight information presented in this TR: (1) acute injury involving soft tissue (Chapter 2),

- (2) acute injury involving the spine (Chapter 2), and
- (3) chronic degenerative diseases of the spine (Chapter 3).

Although this TW is primarily interested in establishing the existence (or lack thereof) of spinal degenerative diseases, acute injuries provide compelling evidence that G levels of the sustained-G environment can traumatize the cervical spine. Also acute neck injuries may predispose the cervical spine or even initiate the development of degenerative disease.

The next and most recent AGARD publication on this topic was published in 1994 'The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High-G' (AGARD-AR-317). This report established the basis for the present publication. AGARD-AR-317 was the culminating product of Working Group 17 that was recommended by the 1989 Symposium (3). The authors of this AGARDograph reviewed the literature extensively (215 references) using their expertise on spinal injury, current and advanced diagnostic procedures, and acceleration physiology. This TR will not review extensively that literature on this topic since the high-G environment and related flying operational procedures have not changed since the publication of the AGARD-AR-317. On the other hand, some information provided in that AR will be used in supporting the arguments presented in this TR.

Indeed it is useful to briefly summarize the recommendations made by AGARD-AR-317 and how those have been impacted by this TW.

1. Spinal study requirements were proposed that included the initiation of research studies on this topic by separate nations and by passive methods such as reviewing existing databases. **Research studies were initiated and databases examined within the purview of this TW.**
2. Aircrew selection using familial history of spinal disease was recommended. **This TW has developed information that supports the implementation of some pilot selection process that includes the spine. Several nations now routinely consider the spine in their pilot selection processes.**
3. Aircrew training that included physical conditioning, proper posture, and restricted mobility of the head during G exposures was recommended. **This TW provides additional supporting data regarding the importance of physical conditioning in preventing spinal injury and the importance of head position during high G exposures.**

4. Improved aircrew education concerning this problem and the importance of lordosis and restricted mobility of the head during high G maneuvers. The TW found evidence that head movement during G exposures directly causes acute neck injuries that may indirectly accelerate spinal degeneration.
5. The importance of reduced weight on the head and improved seat configurations were recommended. This TW has developed information supporting the importance of reduced weight on the head that is calculated with a model developed herein.
6. Research requirements were recommended that included the development of information on head-neck mobility during G, improved spinal function evaluation techniques, and improved spine strengthening exercise programs. The TW has information on new evaluation techniques and on the importance of neck strengthening.
7. Recommended the establishment of a Technology Watch on this subject, which resulted in the formation of this Technology Watch and the publication of this RTO Technical Report.
8. The importance of having another AGARD Symposium on this subject before the turn of this century was noted. That appears to have been compromised with the reorganization of AGARD. However this TR may provide sufficient current information on this topic that will reduce the need for having another symposium on this subject in the near future. Indeed this TR recommends (Chapter 14) a symposium on this specific subject 10 years hence. However in 1999, RTA has scheduled a Symposium 'Accelerated Aging from Repeated Exposures to Occupational Environments' that serendipitously relates to this subject.

1.4 REVIEW OF CURRENT LITERATURE

Literature concerning spinal injury and other relevant information that were published immediately before and after the publication of AGARD-AR-317 were collected by the TW membership and are now presented below, listed as annotated references in alphabetical order of the first author's last name. The information contained in these references was reviewed in detail and is used as the basis for Chapters 2 and 3 in this TR. These references are included in the reference section of this TR, with many other references, by number and referenced throughout the text using those numbers.

Aghina, J. C. F. M. Low back pain and low level flying. Thesis. 1989.

Review of the literature and survey of F-16 pilots revealed a correlation between flying and Lower Back Pain. Fatigue, poor posture, and cockpit seating were major contributing factors. Improved physical conditioning and relaxation of back muscles were considered important preventative measures.

Andersen, H.T. Neck injury sustained during exposure to high-G forces in the F16B. *Avia. Space Environ. Med.* 59:356-358, 1988.

High G maneuvers caught a rear-seat aircrewman unawares that resulted in an acute injury of the C₅-C₆ ligaments and a possible compression fracture of the C₆ vertebra.

Burns, J. W., Loecker, T. H., Fischer, J. R., Bauer, D. H. Prevalence and significance of spinal disc abnormalities in an asymptomatic acceleration subject panel. *Avia. Space Environ. Med.* 67:849-853, 1996. Spinal MRIs of 22 asymptomatic male G research panel subjects with significant high-sustained G exposures were compared with 19 age, sex-matched controls. No significant differences in spinal abnormalities were found between the 2 groups however spinal disk abnormalities were identified in most of the subjects (79 - 91%).

Conley, M. S., Stone, M. H., Nimmons, M., Dudley, G. A. Specificity of resistance training responses in neck muscle size strength. *Eur. J. Appl. Physiol.* 75:443-448, 1997.

Resistance (isometric action of the neck) training does not produce neck muscle hypertrophy nor increase in strength as shown with head extension resistance training.

Hamalainen, O. Flight helmet weight, +Gz forces, and neck muscle strain. *Avia. Space Environ. Med.* 64:55-57, 1993.

Cervical erector spinae muscle strain of 2 fighter pilots each wearing different weight helmets with oxygen masks was determined with EMG. At 7 G %MVC was 20.2% for the heavier helmets (1940-1890 gm) and 17.1% for the lighter helmets (1310 gm).

Hamalainen, O., Vanharanta, H. Effect of Gz forces and head movement on cervical erector spinae muscle strain. *Avia. Space Environ. Med.* 63:709-716, 1992.

A study of 10 fighter pilots found that a major neck extensor muscle during G exposure and with twisting motions reached 100% of the MVC. At 7 G the muscle strain was increased 5.9 fold over 1 G comparisons. The authors noted that this much muscle strain will predispose cervical disks to injury during G exposures.

Hamalainen, O., Vanharanta, H., Bloigu, R. Determinants of +Gz-related neck pain: A preliminary survey. *Avia. Space Environ. Med.* 64:651-652, 1993. Sixteen of 22 (73%) student pilots who did not experience acute inflight neck pain had performed frequent muscle endurance training (no specific neck training) whereas 4 of 5 (80%) who had not trained experienced pain.

Hamalainen, O., Vanharanta, H., Bloigu, R. +Gz-related neck pain: A follow-up study. *Avia. Space Environ. Med.* 65:16-18, 1994.

Of a group total of 66 young fighter pilots, 25 (37.9%) had experienced some in-flight neck pain. The incidence of in-flight neck pain was directly related to the total number of flight hours. General muscle endurance training appeared to have only a minor (if any) beneficial effect on prevention of neck injury.

Hamalainen, O., Vanharanta, H., Kuusela, T. Degeneration of cervical intervertebral disks in fighter pilots frequently exposed to high +Gz forces. *Avia. Space Environ. Med.* 64:692-696, 1993.

Twelve male senior fighter pilots compared with 12 age-matched non-flying controls were found to have significantly higher disk degeneration (88% compared to 64% in the C₃-C₄ disk and 67% to 50% in the C₄-C₅ disk) but not statistically significant. Other cervical disks also showed greater degeneration in pilots.

Hamalainen, O., Tuomo, V., Kuronen, P., Vanharanta, H., Visuri, T. Cervical disk bulges in fighter pilots. *Avia. Space Environ. Med.* 65:144-146, 1994.

A clinical study found 3 fighter pilots who had neck pain during ACMs were subsequently diagnosed with cervical disk bulges.

Hamalainen, O., Vanharanta, H., Hupli, M., Karhu, M., Kuronen, P., Kinnunen, H. Spinal shrinkage due to +Gz forces. *Avia. Space Environ. Med.* 67:659-661, 1996.

Body height of 20 junior fighter pilots was reduced by an average of 4.9 mm after 40 min of maneuvering at high G. This level of shrinkage is comparable to 25 min of weight lifting. Spinal compression could result in some form of disk trauma.

Hamalainen, O., Vanharanta, H., Heinijoki, H. Neck training and +Gz-related neck pain: a preliminary study. *Mil. Med.* 163:707-708, 1998.

Dynamic strength training three times each week reduced the number of workdays lost due to neck injuries/pain over a period of one year in a group of fighter pilots.

Hamalainen, O. Fighter Pilot's Neck Pain. Ph D Dissertation. Univ. of Oulu, Oulu, Finland. 1993.

Extensive review of studies conducted by the author and associates on the subject of the title. Several of those studies have been published and are cited above. The author contributes Chapter 10 of this TR on additional research he and his associates have conducted on this topic.

Harms-Ringdahl, K. On assessment of shoulder exercise and load-elicited pain in the cervical spine. *Scand. J. Rehabil. Med.* 40 pages, 1986.

Extreme neck flexion provides a mechanical load on passive joint or spine connective tissue structures rather than on muscles, which may lead to cervical spine disorders.

Harms-Ringdahl, K., Ekholm, J., Schuldt, K., Linder, J. Neck problems in the Air Force: Cervical spine sagittal load and muscular strength. *Biomech.* 5:9-21, 1991.

Isometric neck extensor strength of 39 jet pilots (mean age of 35 yrs) measured during G while flying aircraft, reached maximum strength capacity at 7 G.

Jensen, M. C., Brant-Zawadzki, M. N., Obuchowski, N., Modic, M. T., Malkasian, D., Ross, J. S. Magnetic resonance imaging of the lumbar spine in people without back pain. *New Engl. J. Med.* 331:69-73, 1994.

Many people without back pain have disk bulges or protrusions but not extrusions of the lumbar spine. This article was the basis for an editorial in this issue "Magnetic resonance imaging of the lumbar spine: Terrific test or tar baby". The editorial noted that the growing literature shows many anatomical abnormalities, including herniated disks, are common in people without back pain.

Kikukawa, A., Tachibana, S., Yagura, S. G-related musculoskeletal spine symptoms in Japan Air Self Defense Force F-15 pilots. *Avia. Space Environ. Med.* 65:269-272, 1995.

89.1% (115) F-15 pilots reported spinal area pain usually in the neck with "check 6". Pain was generally musculoskeletal and neck strength training was helpful in its prevention in 62% of the pilots.

Kluskowski, K., Talar, J., Klossowski, M. Back pain in military jet pilots. *Medycyna Lotnicza, Mojskowy Instytut Medycyny Lotniczej.* 120-121:85-93, 1993.

The authors estimated the range of back pain syndromes. Their assessment is based on a survey and spondylfogniometric studies, carried out in 74 military jet pilots (of MiG-21, MiG-23 and MiG-29). Their results show that both limited spine mobility and pain are more common in older pilots and may not be directly associated with flying high-performance jet planes (e.g. MiG-29).

Kortschot, H. W. Neuro-otological Dysfunctions in Rear-end Car Collisions. Thesis from the Vestibular Department, ENT Clinic, University of Amsterdam, The Netherlands. Printed in English. 95 pages with 98 references. A review of the literature. 1995.

There may be similarities in the mechanisms between cervical spine injuries resulting from rear-end car collisions with those from high sustained repeated G from high performance aircraft.

Makela, J. P., Hietaniemi, K. Neck injury after repeated flexions due to parachuting. *Avia. Space Environ. Med.* 68:228-229, 1997.

C₇ disk degeneration and severe spondylosis with symptoms developing during parachuting while checking the canopy opening. Authors noted similarities with spinal degeneration associated with high-sustained G exposures in fighter pilots.

Mason, K. T., Harper, J. P., Shannon, S. G. Herniated nucleus pulposus: Rates and outcomes among U.S. Army aviators. *Avia. Space Environ. Med.* 67:338-340, 1996.

The incidence of herniated nucleus pulposus (HNP) in army aviators has increased 5-fold during the time period 1987 to 1992. Increased age was considered a possible factor since army pilots have increased in mean age over that time period.

Mestre-Moreiro, M., Cañizal-Garcia, M. Barcena-Orbe, Rios-Tejada, F. Cervical herniation in fighter pilots. Meeting Proceedings of 'Reunion Hispano lusa de Neurocigugia', Lisbon, May, 1998.

Two fighter pilots experienced acute cervical disk herniation of C₆₋₇ as a result of increased sustained G exposure. One pilot with disk degeneration of the C₃₋₄ and C₅₋₆ had a history of re-occurring neck pain during aerial combat maneuvers.

Newman, D. G. Cervical intervertebral disc protrusion in an RAAF F-111C pilot: A case report. *Avia. Space Environ. Med.* 67:351-353, 1996.

Disk protrusions of C₆₋₇ was seen on MRI and narrowing of spinal canal at C₅₋₆ level also with CT-myelogram. Associated repeated 4 G air to ground maneuvering was considered as a possible contributing factor. The author notes the importance of helmet weight, neck muscle training, and pre-mission neck warm up.

Newman, D. G. Head positioning for high +Gz loads: An analysis of the techniques used by F/A-18 pilots. *Avia. Space Environ. Med.* 68:732-735, 1997.

Various methods for protecting the cervical spine are used by pilots of high performance aircraft. Importance of this survey is that pilots are aware of the potential for neck injury during high-G exposures. The author makes a point that such positioning

strategies along with neck muscular strength exercising training are important in preventing cervical injuries.

Newman, D. G. +Gz-induced neck injuries in Royal Australian Air Force fighter pilots. *Avia. Space Environ. Med.* 68:520-524, 1997.

85% (n = 44) of F/A-18 pilots reported some form of neck injury during high G maneuvers. Neck exercises were believed to be helpful.

Oksa, J., Hamalainen, O., Rissanen, S., Myllyniemi, J., Kuronen, P. Muscle strain during aerial combat maneuvering exercise. *Aviat. Space Environ. Med.* 67:1138-1143, 1996.

Muscle strain from the thigh, abdomen, back and lateral neck was measured on 6 fighter pilots during ACM. Mean % maximum voluntary contraction (% MVC) was highest in the neck muscle 19.8% however all muscles exhibited > 100% MVC in at least one pilot during one ACM. The highest was 257% MVC, found in a lateral neck muscle injury that terminated the engagement.

Petren-Mallmin, M., Linder, J. Magnetic resonance findings in the cervical spine of experienced fighter pilots and controls. Abstract. *Aviat. Space Environ. Med.* 65:470, 1994.

Sixteen male experienced male fighter pilots had significantly greater incidences of disk protrusion and osteophytes on the posterior border of vertebral bodies compared to 15 age/sex matched controls. Other degenerative changes were increased in the pilot population but were not statistically significant. Conclusion was that fighter pilots are at an increased risk of cervical spine degeneration.

Popper, S. E., Morris, C. E., Briggs, J., Fisher, F. Comparison of acceleration subjects to other populations: Spinal anomaly distribution. *Avia. Space Environ. Med.* 68:426-431, 1997.

Spinal abnormality data from human research acceleration panels are compared with similar pilot data from several countries. May have some control-type data of value for comparison of cervical spine degeneration with repeated sustained acceleration exposures.

Schall, D. G. Non-ejection cervical spine injuries due to +Gz in high performance aircraft. *Avia. Space Environ. Med.* 60:445-456, 1989.

Reported on 8 cases of acute spinal injury of fighter pilots from specific high G exposures, usually with necks unexpectedly caught in rotated positions. Of those 8 injuries, 2 were vertebral compression fractures and 3 were disk herniation injuries.

Tejada, F. R., Cuevas, A., Esteban, F., Azofra, J., Fernandez, R., Mendez, A. Magnetic resonance imaging of the cervical spine in high performance aircraft pilots of the SAF. 66th An. Mtg. Aerosp. Med. 7-11 May, 1995.

Seventeen fighter pilots were compared with 22 age-experience matched controls (cargo pilots) MRI and X-ray of spines. Data suggest that more severe spinal disk abnormalities occur at the C₅-C₆ level in fighter pilots.

Travis, T.W., Morgan, T.R. U.S. Air Force positive-pressure breathing anti-G system (PBG): Subjective health effects and acceptance by pilots. *Avia. Space Environ. Med.* 65:A75-A79.

An anonymous survey of F-15 and F-16 pilots with and without PBG during various sorties reported significant reduction in acute neck soft tissue injuries while using PBG.

Trousset, A., Grapperon, J., Maugey, B., Gommeaux, H. Conditionnement musculaire cervical chez le pilote de chasse. Etude préliminaire sur 8 pilotes de l'aviation de chasse embarquée. *Med. Aeronaut. et Spat.* 33:133-138, 1994.

Cervical muscular conditioning program of 1 month with 8 subjects in the experimental group and 8 as controls increased the strength of the lateral flexor muscles.

Van Leusden, A. J., Prendergast, P. R., Gray, G. W. Permanent grounding and flying restrictions in Canadian Forces pilots: A 10 year review. *Avia. Space Environ. Med.* 62:513-516, 1991.

Of those permanently grounded or with restrictive flying status (258 pilots of all types of aircraft) over 10 years, 17% were from orthopedic disorders of which 40% were disk disease. Lower back pain was most common and the authors recommended the introduction of a program of back-care education.

Van Leusden, A. J., van Dalen, B. Pre-employment screening for back problems in pilot candidates; the necessity of radiological examinations. *SAFE J.* 27:100-103, 1997.

Two hundred sixty nine pilot candidates using both clinical and radiological findings were screened for spinal disorders. Data confirmed that findings from each type of examination were correlated indicating that both types of examinations are important in screening pilot candidates for flying high performance aircraft.

Vlassov, V. V. Number of chronic conditions and professional longevity of aviators. *Avia. Space Environ. Med.* 68:373-377, 1997.

A 1980-1988 medical database of chronic medical conditions of 1534 Russian pilots/navigators found

14% with spinal disease. Spinal disease was the least common cause of reducing aviator longevity. Aviators were mixed transport, bomber and fighter types.

Vogue, V. M., Toland, G. A survey of centrifuge subjects assessing the relationship between repeated +Gz exposures and chronic back pain. *SAFE J.* 26: (2) 47-52, 1996.

A retrospective survey of 20 research acceleration panel subjects found no increase in chronic back pain or injury in the study group. Back pain was related to the use of tobacco and subject height.

Yacavone, D. W., Bason, R. Cervical injuries during high G maneuvers: A review of Naval Safety Center data, 1980-1990. *Avia. Space Environ. Med.* 63:602-605, 1992.

The reported incidence of muscle strains of the neck has increased primarily in pilots of fighter aircraft (e.g. F-18). The use of lighter weight helmets and muscle strengthening exercises appear to be helpful in its prevention.

Ziyan, W., Qijiu, L., Zhu, L. Analysis of radiographic screening of fighter pilots' cervical vertebrae. *Chin. J. Aerosp. Med.* 9:117-119, 1998.

Radiographs of cervical vertebrae of 116 active fighter pilots were compared with 62 ground-crew controls. Abnormalities of the spine indicating degeneration was 47.4% in the pilots and 22.6% in the controls (P < 0.01). Age and flying time were closely correlated with spinal degeneration.

1.5 REPORT OF THE FINAL TW MEETING (ROTTERDAM, NE)

In addition to the foregoing information, several reports, many of which were ongoing studies on this topic, were presented by national representatives at the concluding TW Meeting held in Rotterdam, NE, 28 September 1997. Other presentations were concerned with that nation's experiences with cervical pathologies associated with repeated sustained G. Therefore, this is the most current information available on this subject. A brief summary of each presentation made at that meeting follows in the order of their briefing. Some of these reports and related information are presented also in that order in considerable detail as separate chapters (Chapters 4 through 12) that follow in this TR.

Holewijn, M., Hendriksen, I. Degenerative changes of the spine in pilots of the Royal Netherlands Air Force. A retrospective longitudinal study of 188 F-16 pilots and 128 low-G control pilots used spinal X-rays and found a significant increase in osteophytic spurring in the F-16 pilots at C₄-C₅ and C₆-C₇ and general

cervical arthrosis deformans. There was no correlation between spinal diseases and flying hours.

Tachibana, S., Hanada, R. Comparative study of F-1 and F-15 Japanese fighter pilots' spines using MRI. Forty-nine F-1 (low G) pilots were compared with 28 F-15 pilots using MRI of cervical and lumbar spines. The only significance was the correlation ($P = 0.03$) between MRI findings and neck pain in the F-15 pilots. The authors interpreted these findings to mean that high-G exposures may not cause spinal degeneration although the small number of F-15 pilots in the study was a limitation.

Pongratz, H., Pippig, T. X-ray study of fighter pilot spines in the German Air Force. F-4 pilots had approximately twice as much spinal disease as transport and lower G pilots but the same amount as helicopter pilots. Lumbar disease was the most common in all groups of pilots.

Harms-Ringdahl, K. Biomechanics of the cervical spine and its modeling. Reported on injuries of cervical musculature in Swedish fighter pilots that may lead to cervical degeneration. Dr. Harms-Ringdahl developed a model on the cervical spine relating forces developed during sustained G with potential for disk degeneration (see Chapter 12).

Stupakov, G. P., Khomenko, M. N., Bukhtiyarov, I. V. Pathological and functional changes of spinal column in flyers of high performance aircraft. Reported that 30% of MiG-29 and Su-27 pilots had acute neck injuries. In a study of 50 Russian high-G pilots (mean age 36.4 years) 17 had osteoarthritic spondylosis of their cervical disks.

Talar, J., Mazurek, K., Klukowski, K., Kwasucki, J., Marek, J., Stepień, A. Review of the vertebral column pain problems in Polish Pilots. Sixty-two aerobatic pilots exposed to +7.5 to -4.5 G_z with a mean age of 26.7 years reported a reduction in spinal mobility after G exposures. Physical therapy reduced this limitation. Survey of 13 pilot groups found that a reduction in spinal mobility directly correlated with age and possibly with high-G exposures.

Tejada, F. R., Herrera, M. C., Garcia, J. A., Garrido, J. V., Diaz, C. V. Role of the magnetic resonance in the evaluation of the cervical spine in high performance aircraft pilots. Twenty-four Spanish F-16 fighter pilots were compared with an equal number of age/G exposure controls using MRI, found increased degeneration of intervertebral disk C₃₋₄ plus changes in the vertebral density 'body signal' at C₅ and C₆.

1.6 FINAL REPORT OF THE TW (SAN DIEGO, CA, US)

A near-final draft of this TR was distributed by the Chairperson, Dr. Russell R. Burton to the membership of the TW. This same draft was provided to all persons in attendance at the 18 Oct 1998 meeting of the TW, in San Diego, CA. This meeting was immediately prior to the RTO Symposium on 'Current Aeromedical Issues in Rotary Wing Operations'. In attendance at this final TW Meeting were Col. Jan Linder (Sweden); Major Olavi Hamalainen (Finland); Maj. Francisco Rios Tejada (SP); Maj. Michel Los, (NL); Col. William Tieleman (NL); Dr. Jean Michel Clere (FR); and Dr. Russell R. Burton, Chairperson (US). Prior to this meeting, copies of the final draft were mailed to the entire TW membership for their review, comment, and suggested changes. As much as possible, all comments and changes that were received by Dr. Burton have been included in this final draft of this TR.

1.7 SOURCES OF INFORMATION FOR THIS TR

The information used in this TR, related to spinal injury from sustained G exposures, was derived from the above sources of information including: (1) AGARD-AR-317 (3); (2) TW obtained published references; and, (3) Reports of ongoing studies and pertinent information on this topic by several nations including presentations at the Sept 97 TW Meeting. Additional information that was used in the preparation of this TR was obtained from various sources with the help of many people and all are listed in the reference section of this TR.

CHAPTER 2

ACUTE NECK INJURIES

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2.1 INTRODUCTION

Acute neck injuries are believed to play a role in degenerative changes of the cervical spine although this relationship is not completely understood (48). The cervical spine is the most vulnerable segment of the human spine because of its principal function of providing mobility to the head. Muscles and ligaments that protect the spine are also involved with moving the head and assist in breathing. However, these muscles and ligaments are limited as to their ability to provide protection to vulnerable structures of the spine; i.e., vertebrae and intervertebral disks. Therefore the cervical spine, because of its structure and mobility requirements, is uniquely more vulnerable to external loading, induced acute injuries and degenerative changes than other segments of the spine. The neck is particularly vulnerable with certain head positions especially as cervical muscles and ligaments are overexerted, fatigued or injured. Indeed, it is clear from several published reports that these muscles and ligaments are commonly overexerted or injured during exposures to high-sustained G (24, 33, 35, 36, 68, 70, 92, 127, 134).

Neck tissue injuries that result from maneuvering G exposures will be classified and therefore discussed in this TR using the method described in AGARD-CP-417 (10): (1) Acute soft tissue, (2) Acute spinal (hard) tissue, and (3) Chronic degenerative (osteophytosis and arthrosis). In this chapter, acute neck injuries only will be examined but discussions concerning their role in degenerative diseases of the cervical spine will be presented.

2.2 ACUTE SOFT TISSUE INJURIES

Acute soft tissue injuries of the neck are identified by their symptoms of pain from exceeding the limitations of muscles and ligaments that protect the cervical spine. Besides this injury criterion, a physiologic criterion of the soft tissues of the neck that measures these limitations is % maximum voluntary contraction (% MVC). (% MVC of a muscle can be quantified by measuring electrical muscle activity using electromyography, EMG). Specifically the

activity of the principal extensor muscle of the neck is most informative. Both of these measures of soft tissue functional capability in support of the cervical spine will be discussed in this section.

The neck supports the head using two anatomical components: (1) soft tissues of the neck principally involve muscles and ligaments, and (2) hard tissue spinal structure composed of vertebrae, intervertebral disks, and supporting bony structures. The principal function of the spine is to protect the spinal cord and support body structure providing for movements of the body. The spine is a passive structure at greatest risk when the soft tissue components that provide support to the spine are compromised with fatigue, weakness or injury. Therefore, in considering degenerative disease of the cervical spine of aircrew of high performance aircraft, it is important to understand the limitations of the soft tissues of the neck that support the cervical spine during sustained G exposures. When these limitations are exceeded neck injuries occur.

2.2.1 Frequency and Nature of Injuries

Soft-tissue injuries of the neck commonly occur during exposures to high-sustained G. The muscle group that provides the greatest support to the cervical spine is the one containing the neck extensors or anti-gravity muscles. The primary neck extensor is the *cervical erector spinae* muscle. Secondary muscles are those involved with head rotation and flexion, which are relatively weak compared with the neck extensors. However, it is important to note that these secondary muscles are used extensively by pilots during aerial combat maneuvers (ACM).

This type of neck injury occurs during flight and can be functionally debilitating at that time. Vanderbeek (127) classified acute neck injuries into 5 categories: (1) simple muscle pain/strain or tenderness, (2) muscle spasm, (3) severe muscle strain with contraction of the cervical muscles with neck twisting, (4) sensory deficits, and (5) motor deficits with deep tendon reflexes or frank motor impairment. The last three categories were considered together as a major

neck injury group. Knudson et al. (70) classified acute neck injuries as pain that did not compromise or did compromise mission effectiveness. Presumably, the latter group would be comparable with the major neck injury category developed by Vanderbeek (127).

Minor acute neck injuries increased by approximately 100% in aircrew of U.S. Air Force modern high-G aircraft (e.g., F-15 and F-16) over lower-G aircraft (F-5). Major neck injuries more than doubled in fighter pilots over 35 years of age compared with the 30-34 year group and tripled over the 20-29 year olds (127). However, considering all acute neck injuries, increasing age did not play a significant role.

On the other hand, the incidence of acute neck injuries was more dependent upon the type of aircraft flown. Vanderbeek (127) found that approximately 23% of F-5 pilots, 50% of the F-15 pilots and 60% of the F-16 pilots had some form of acute neck injury during the last 3 months. In F-16 pilots, 23% of those with neck injury were classified as having a major neck injury whereas in the F-15 only 11% had a major neck injury.

Knudson et al (70) reported 74% of FA-18 pilots with acute neck injuries during their entire flying history with more than 50% major neck injury. Later surveys by Kikukawa et al. (68) of F-15 pilots and Newman (92) of F/A-18 pilots reported higher incidence rates of acute neck injuries; i.e., 89% and 85% respectively. A summary of acute neck injuries related to types of aircraft flown is shown in Table 2-1.

Table 2-1: Incidence (%) of Acute Neck Injuries of Pilots of Various Aircraft During Their Careers.

Low G	Mod G	F-15	F-16	F-18	Ref
	30.7 ¹	51.2	57.5		127 ⁷
	30 ² /58 ³			74	70
	82 ⁴			85	92
14.8 ⁵	30 ⁶	95			68
	38 ⁸				33, 36

¹F-5; ²A-7; ³A-4; ⁴Macchi MB326H; ⁵F-1; ⁶F-4; ⁷

Injuries past 3 months; ⁸ HW MK 51.

Ligamentous injuries of the neck during G exposures have been reported by Andersen (6), Newman (90) and Schall (108). Andersen (6) reported ligament injuries of the C₅-C₆ and a possible compression fracture of C₆ that resulted from a high G maneuver that the aircrew in the back seat did not expect. (Unexpected high-G maneuvers frequently precludes contraction of neck extensor muscles in support of the cervical spine.) Newman (90) reported the displacement of the longitudinal ligaments of the C₆-C₇ disk in a pilot flying air to ground, repeatedly exposed to 4 G. Schall (108) documented the

occurrence of a C₆-C₇ ligament disruption at 4.5-5.5 G with head rotation while checking his 5 o'clock position.

2.2.2 Contributing Factors

2.2.2.1 Age and Flight Hours

Although increasing age appears to be significantly and directly correlated with a decrease in spinal mobility (Figure 9-1), its effect on acute neck injury is less clear. Vanderbeek (127) reported an increase in acute major injuries to the neck in fighter pilot groups 35 years of age and older but no differences in minor acute neck injuries.

Hamalainen et al (36) reported on 17 parameters as they related to acute inflight neck pain. They found that total flight hours was the only parameter that was significantly correlated.

2.2.2.2 G-Level

Even though acute neck injuries have increased substantially with a greater use of higher-G aircraft, these types of injuries also occur frequently at lower G levels. Newman (92) reported the greatest number of injuries occurred at 4 and 5 G in pilots of the F/A-18 capable of 8 G. It is not clear why lower G levels have such a high incidence of neck injuries. This fact is particularly difficult to understand considering that pilots flying aircraft during WW II who routinely flew at 5 and 6 G did not report neck injuries but instead seemed to have had more lumbar injuries (114). Perhaps pilots of modern fighter aircraft move their heads more during lower-G level exposures with canopies that provide greater visibility. It is far more difficult (i.e., at times impossible) to move the head at very high G levels. Head movement during G significantly increases chances of neck injury (see Chapter 12 on biomechanics of the cervical spine, Figures 12-6 and 12-7). On the other hand Hamalainen et al (35) concluded that a minimum of 4 G was necessary to cause cervical injuries.

2.2.2.3 Muscle Strength

Hamalainen and Vanharanta (34) measured electrical activity of the *cervical erector spinae* muscles (major neck extensor muscle) during in-flight maneuvers at various G levels and with head movements. Relative maximal voluntary contraction (% MVC or relative muscle strength capability) of this muscle was evaluated using this technique. The mean extensor muscle strain was increased 2.4 times (above baseline-control values) at 4 G and 5.9 times at 7 G. In one subject, 100% of the MVC was reached in both right and left extensors at 7 G. The mean % MVC values for 10 pilots at 7 G (without head movement) were 36% for the left and 40% for the right neck extensor. With head rotation at 4 G, the % MCV increased to a mean of 80% with head rotation and 56% with head

flexion/extension movements. One pilot with head flexion/extension had 110% MVC of the left extensor and another pilot had 190% MVC of the left extensor during head rotation at 4 G. Muscles that generate > 70% MVC have a substantially increased risk for acute injury.

Oksa et al (93) measured the % MVC on muscles of the thigh, abdomen, back, and lateral neck of 6 fighter pilots during 5 to 7 episodes of 3 min-ACMs between 3.5 – 7 G. The mean % MVC for all muscle activity ranged from 5.2 % for the thigh to 19.8% for the lateral neck. All muscles, at least one time on one pilot, exhibited > 100% MVC. The maximum % MVC for the thigh (*m. rectus femoris*) was 170%; abdomen (*m. rectus abdominis*) – 142%; back (*m. erector spinae*) – 255%; and lateral neck (*m. sternocleidomastoid*) – 257%. The hyper-contraction of that lateral neck muscle of 257% MVC resulted in an injury of that muscle forcing the pilot to return to base.

Harms-Ringdahl et al. (56) studied fighter pilots who had experienced neck pain during G exposures and those who had not had pain. Those with a pain history had less than average neck-muscle endurance strengths. They reported that cervical extensor muscles reach their maximum strength capacity at 7 G supporting the findings of Hamalainen and Vanharanta (34) and Oksa et al (93).

Increasing neck muscular strength occurs with dedicated neck or whole body muscle exercise regimens. There is some evidence that an increase in neck muscular strength reduces the incidence of acute soft tissue neck injury during G exposures (21, 35, 36, 68, 90, 91, 123, 134). Unfortunately there have not been control studies that have shown a direct relationship between neck muscle strength and a reduction in acute neck muscle injury.

A neck muscle warm-up regimen before exposure to the high G environment is considered helpful in preventing neck injury (90, 127). These findings provide evidence of the importance of muscular support in protecting the neck from acute soft tissue injury. The importance of this relationship in women pilots with less muscular necks is unknown. Moroney et al (87) reported on 4 women subjects that their mean neck strengths were 60-90% of men.

2.2.2.4 Head Position

Head movement, particularly the 'check six' position during sustained G exposures is frequently involved with acute in-flight injuries (68, 70, 91, 127). Head movement or rotation significantly increases the % MVC requirements of neck extensor muscles and involves other muscles that are comparatively weak (34). The majority of fighter pilots position their heads prior to onset of high G to protect themselves from

neck injuries (91). This head positioning effect on neck injury provides indirect evidence relating muscular function failure with neck injury.

In Chapter 12, the biomechanics of head position relative to the changing load moment on the cervical structures including the muscles, ligaments, and vertebral joints is modeled. Implications are clear that head positions assumed by the fighter pilot during the ACM can place extreme strain on neck muscles and ligaments; i.e., greatly increasing risk of injury.

2.2.2.5 Life Support Equipment

Flight-helmet weight is directly related to the incidence of soft-tissue injury of the neck (90, 134), although Hamalainen (33) found reducing helmet weight to be of '... limited value in preventing in-flight acute neck pain and related problems'. He measured % MVC of the *cervical erector spinae* of two fighter pilots wearing helmets of different weights. At 7 G the lighter-weight helmet (1310 g) resulted in a 17.1% MVC and the heavier helmet (1940 g) produced a 20.2% MVC. He concluded that helmet ergonomics, including helmet weight reduction, could be beneficial in some pilots particularly during high-G ACM.

Interestingly, Travis and Morgan (122) reported that the use of positive pressure breathing during (PBG; e.g., Combat Edge Ensemble), with similar head weight to the standard helmet/mask ensemble, decreased acute neck soft tissue injuries in pilots during ACM. They reasoned that decreased fatigue and better head positioning might play a role in this reduction in neck injuries. Also since certain cervical muscles are involved in breathing, PBG reduces the intensity of the anti-G straining maneuver (AGSM) that requires a high level of % MVC of breathing muscles. Therefore these cervical muscles would use less % MVC during an ACM with less chance of injury and be more supportive of the head during increased G.

2.2.3 Summary and Conclusions

Injury of the soft tissues of the neck commonly occurs during sustained G exposures. This injury is directly related to the increased G-forces that exceed the limitations of the muscles of the neck in support of the head. These limitations are exceeded because of insufficient extensor strength and/or muscle function capabilities of the support structure of the neck especially with a head rotation position in combination with extension/flexion. The report by Andersen (6) illustrates this relationship with the rupture of a neck ligament from an unexpected G maneuver that resulted in a probable vertebral fracture documented with X-ray. Head movement or rotation of the head can decrease neck muscle functional strength by 50% and increase the load moment

induced by the weight of the helmet allowing neck extensors to be maximally contracted at 4-5G. This situation was documented by Schall (108), using X-ray, finding a C₆-C₇ ligament disruption following a 4.5-5.5 G maneuver with head rotation while checking 5 o'clock. Similarly, Newman (90) reported the same ligament injury at 4 G.

Soft tissue functions/injuries of the neck appear to be related to acute spinal injury and degenerative cervical spine disease because:

(1) external forces generated by the high-G environment routinely exceed the spinal protection afforded by neck muscles and ligaments, and,

(2) injury to the muscles of the neck reduces their strength and thereby reduces their protective capability for the cervical spine.

It is reasonable to assume therefore that sustained G, particularly with head movements/positioning by the pilot during operations, can provide the environment conducive to acute cervical spinal injury and perhaps the potential for initiating degeneration of the cervical spine.

2.3 ACUTE HARD TISSUE (SPINAL) INJURIES

In the previous section on acute soft tissue injuries, it was argued that the soft tissues of the neck provided the primary protection for the cervical spine. Further, it was found that soft tissues routinely exceeded their maximum support capabilities during sustained G exposures that resulted in their injury. Also it was concluded that these injuries further reduced their ability to protect the cervical spine. Consequently, acute injury to the hard tissues of the neck (spine) would be expected to occur during relatively high G exposures, especially with soft tissue injury; e.g., during head rotation. Indeed several acute spinal injuries have been reported and under circumstances that suggested the soft tissues were overloaded and damaged at the same time as was the spine.

2.3.1 Nature of Injuries

Andersen (6) reported ligament injuries of the C₅-C₆ and a possible compression fracture of C₆ that resulted from a high G maneuver that the backseater did not expect. The unexpected nature of the maneuver prevented the person from contracting their neck extensor in preparation for the onset of G. This complex injury suggests that neck muscle failure probably precipitated the spinal injury.

Schall (108) published the most comprehensive article on spinal injuries from sustained G exposures. His report covered 5 different acute spinal injuries that occurred during high G maneuvers. Brief summaries of the different types of injuries follow:

1. Two cases of compression fractures occurred. One case involved C₇ and the other C₅. The former was the result of involuntary neck flexion at 9 G because the neck muscles were unable to keep the head extended. The latter involved flexor/extensor head movement at 6.5 G.
2. Two cases of herniated disks occurred with G maneuvers. One involved the C₅-C₆ disk and the other the C₆-C₇ disk. The former occurred while rotating the head to check 6 during an 8.4 G maneuver. The latter occurred with rotation and flexion/extension of the head during a 9 G maneuver.
3. A fracture of the spinous process of C₇ was associated with an unexpected 5 G climbing turn.

Clark (19) describes the history of an F-14 pilot that during an increased G maneuver, developed neck pain that persisted for several months. The G level was not known but the injury occurred during a defensive maneuver against an F-21 Mirage. A Magnetic Resonance Imaging (MRI), Computer Axial Tomography (CAT) Scan, and myelogram showed a bulging disk of the C₃₋₄.

Newman (90) reported on a pilot who flew several 4 G air to ground maneuvers. Following several weeks of these types of maneuvers, he reported right neck and shoulder pain. A MRI showed right-sided protrusion of the C₆-C₇ disk with displacement of the longitudinal ligaments. This situation is interesting in that it provides evidence that repeated low-G exposures resulted in a disk protrusion initiating a degenerative lesion of the spine. In addition, this injury appears to be a result of the failure of the soft tissue with the ligament disruption shown on the MRI. Muscle fatigue may have been a factor as air-to-ground maneuvers are repetitive with the head positioned in the same direction.

Hamalainen et al (38) reviewed 3 case reports of pilots who suffered bulging cervical disks associated with acute inflight neck pain during ACM. The first pilot had neck pain at 7 G with C₅₋₆ disk bulging. The second pilot was injured at 6.7 G that involved the C₆₋₇ disk. The last pilot suffered neck injury at 7.2 G with bulging of the C₃₋₄ and C₆₋₇ disks.

Mestre-Moreiro et al (86) reported on acute disk herniations of two pilots involving the same C₆₋₇. One pilot, 36 years of age, experienced an unexpected 7 G exposure with the head in a check six position. The other pilot, 38 years of age, experienced acute neck pain during a 5 G maneuver with his head rotated and slightly flexed. He had a history of neck soreness during increased G exposures. This neck soreness

during aerial combat maneuvers indicates that the neck muscles had been repeatedly injured and apparently were not capable of fully protecting the spine from G-induced injury. Therefore, the acute spinal injury was not unexpected of the second pilot. This pilot went on to develop degenerative cervical disk disease (reported in Chapter 3).

2.3.2 Similar Injuries from Different Environments

Similar acute spinal pathologies exist with exposure to rear-end car collisions; i.e., the author comparing similarities of cervical pathologies with repeated high-sustained G (72).

Scher (110) reported similar spinal injuries in workers who had accidents while carrying heavy loads on their heads.

2.3.3 Summary and Conclusion

Acute injuries to the hard tissues of the neck (i.e., the cervical spine) occur during various types of G maneuvers. All such injuries occurred when the soft tissues were at increased risk of injury impairing their ability to protect the spine. In two cases, soft tissue injury was documented occurring with hard tissue injury.

The same cervical vertebrae and associated disks (C₅-C₆-C₇) were affected in all of these reports of acute injuries suggesting a similar etiology. Generally, acute cervical injuries occur most commonly during flexion and in the region of the C₄₋₅ and C₅₋₆ levels (110). These vertebrae are also common sites for degenerative changes from aging and represent points of greatest flexion of the neck (see Chapter 12).

These acute spinal injuries provide evidence that G forces at operational flying levels can acutely inflict pathologies of the type that have been identified with degenerative changes of the spine. Additionally, these injuries appear to have occurred with the failure of the support provided by the soft tissues of the neck; i.e., muscles and ligaments. Acute soft tissue cervical injuries do not frequently result in acute spinal injury. On the other hand, it can be argued that without soft-tissue protection, the spinal disks would be repeatedly traumatized producing subacute lesions eventually leading to degenerative spinal disease.

2.4 PREVENTION OF ACUTE NECK INJURIES

2.4.1 Mechanical Devices

The acute neck injury problem has drawn attention to the idea of using neck support devices that would provide alternative load paths from the head to the shoulders during increased sustained G. This approach has developed inflatable and mechanical devices that are activated at high G levels providing increased support for the head. However these

systems restrict head movement that at times can be a necessity even during increased G.

Other systems have been considered including one that is activated only when head movement is too rapid to be controlled (involuntary) (103). This approach would probably reduce acute neck injury of the soft tissue from involuntary rapid head movements, but would not be effective in reducing external loads on the spine during increased G without head movements. Muscle and ligament strains during increased G exposures will occur without rapid head movements.

2.4.2 Neck Muscle Strengthening and Warm-up

Strengthening neck muscles with physical conditioning is considered to be useful in reducing acute neck injuries with increased G exposures. The basis for this approach is that % MVC of certain neck muscles exceed 100% during most exposures to increased G. Increasing neck muscle strength will reduce the % MVC used during G exposures.

Pilots are advised to warm-up their neck muscles prior to G exposure, like all athletes do before physical competition.

2.4.3 Limiting Head Movement

Eliminating/reducing head movement during increased G exposures is considered most important in reducing acute neck injuries. Head mobility (rotation and extension/flexion) during G significantly increases the risk of neck injury. For this reason fighter pilots are advised not to move their heads during sustained G exposures; i.e. > 4G (127). Most pilots position their head prior to the onset of G keeping that head position stable until the off-set of G (91).

CHAPTER 3

DEGENERATIVE DISEASES OF THE CERVICAL SPINE

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3.1 INTRODUCTION

Degenerative diseases of the spine normally occur with aging. These changes are primarily vertebral spurring called osteophytes and degenerative changes of increased density of intervertebral disks and narrowing between vertebrae. Degenerative diseases of the cervical spine from aging usually affect C₄₋₅₋₆₋₇ vertebrae and associated intervertebral disks. Disk C₅₋₆ is the most common location with C₄₋₅ and C₆₋₇ next most commonly involved disks (28, 29, 115). The incidence of some form of cervical spinal degeneration (with or without symptoms) increases significantly and directly with increasing age (28, 29, 61).

Unfortunately, there is scant direct evidence of degenerative diseases of the spine associated with repeated exposures to sustained G. The conclusion reached with AGARD-AR-317 was that there was insufficient information available to substantiate a causal relationship between repeated exposures of sustained G and degenerative diseases of the spine(3). However since that time, several studies and reports have been published that support the theory of a causal relationship. These will be reviewed in this chapter. Specific studies conducted in association with this TW will be included as separate chapters that immediately follow this chapter.

In Chapter 2, it was established that even moderate levels of G exposures cause soft tissue neck injuries that reduce the protective nature of the muscles and ligaments of the neck. Under higher sustained G levels, greater numbers of acute spinal injuries occur. These cervical injury sites are at the same locations as degenerative diseases from other conditions.

Little is known concerning subacute injuries of the cervical spine which involve intervertebral disks. Increased loading of the neck may well cause such undetected injuries. It is known that these types of injuries can initiate degenerative diseases of the spine (see Chapter 12). Consequently, it appears that the spine may be at increased risk for developing

degenerative diseases with repeated exposures to sustained G. Indeed, under certain previously described circumstances, some form of degenerative disease of the spine should be expected.

3.2 SPECIFIC INCIDENT OF DEGENERATIVE DISEASE WITH CHRONIC NECK INJURY

Mestre-Moreiro et al (86) reported a medical case of a fighter pilot with a history of neck soreness during increased G exposures indicating chronic cervical muscle injury. This pilot suffered an acute C₆₋₇ disk herniation during a 5 G maneuver. A MRI of the acute injury found degenerative disk disease of the C₃₋₄ and C₅₋₆. The chronic neck muscle injury supports the notion that cervical muscles are important in protecting the bony tissues of the spine from G-induced injury.

3.3 SPECIFIC STUDIES OF DEGENERATIVE DISEASES OF PILOTS

3.3.1 Vertebrae and Intervertebral Disks

Four studies have been published on degenerative diseases of vertebrae and intervertebral disk of pilots of high performance aircraft. All of these studies have been cross-sectional with age-sex matched controls with no G exposure.

Gillen and Raymond (31) reported on thirty-one fighter pilots and 13 controls matched for sex and age. These were compared for range of motion measurements and spinal X-rays of the neck. Pilot participation was voluntary, with 71% having experienced neck pain from in-flight G exposures. Populations were studied in age groups of 20-29; 30-39; and 40-55 years. Range of motion of the neck was reduced by 25% in the 20-29 and 30-39 year-old groups of pilots in comparison with the controls. No differences were found in the older group. Spurring of the C₅ and C₆ vertebrae was significantly greater in the pilot population of all three age groups suggesting an accelerated aging process for the pilots. Narrowing of the intervertebral spaces of C₄₋₅ and C₅₋₆ was

significantly greater in the pilot population. The authors stated in discussing their results that spurring from stress, strain, and injury from flying most commonly occurs on the C₄, C₅, and C₆ vertebrae.

A significant problem with this study was the small number of controls used; i.e., the 20-29 year old group had only one control compared with 8 pilots. Since age is a major factor in measuring degenerative changes of the neck, comparable numbers of controls are an important consideration in conducting and evaluating any study of this type. Another problem with this study is the involvement of 5 pilots with a history of forced landing or ejection that could have produced spinal injuries that were undetected. The authors noted that some neck symptoms had occurred as a result of those events.

On the other hand, the involvement of pilots, the majority of which had had prior symptoms of neck pain from exposures to sustained G exposures, makes this study appropriate for examining degenerative diseases of the cervical spine. It is reasonable to assume that selecting only pilots who never had symptoms of neck injury would have involved a population of pilots who demonstrated above average tolerance to acute neck injuries. These very tolerant pilots could perhaps have less chronic degenerative diseases of the cervical spine. Of course this supposition requires the existence of a causal relationship with acute cervical pathologies.

Hamalainen et al. (37) published a cross-sectional study on degenerative diseases of the cervical spine of fighter pilots that focused entirely on disk disease. The 12 male subject-pilots were approximately 36 years of age with many hours of ACM during the immediate previous 10 years. Eleven (92%) of the pilots had reported prior incidents of acute neck pain during flight. Thus their pilot group was representative of the normal pilot population with most subjects at increased risk for degenerative diseases. Two radiologists graded the level of intervertebral disk disease from 0 (normal) to 6 (disk bulge compressing the spinal cord) using MRI. Agreement of grading between the readers was good.

The age-matched control group showed the occurrence of mild to severe level of degenerative disease of the C₃₋₄ through C₆₋₇ disks in the majority of subjects. As expected C₅₋₆ and C₆₋₇ had the highest level of disease including more moderate changes. In spite of the high level of age-related disk degeneration in the controls, the pilot group had increased incidence of disk disease at all levels except for C₅₋₆ with 86% occurrence of disease in the controls. Indeed, only disk degeneration of the C₃₋₄ disk was statistically higher in the pilots for all levels of disease.

When the moderate levels (grades 3-4) were extracted from the overall disk changes, the incidence rates for all disks were reduced except for the C₃₋₄ of the pilot group which remained at 88% compared with the control group rate of 36%. Extracting the mild and severe changes (moderate disk changes, Table 3-1) from all groups showed that the pilot group had increased incidences though not statistically significant for all levels of cervical disks.

Interestingly, the investigators did not include subjects with severe changes when they extracted the mild disk changes in the moderate disk change group (Table 3-1). When the severe changes were included with the moderate changes in Table 3-1, using the data shown in 'All Disk Changes Group', the moderate disk changes for C₄₋₅ substantially increased the percentage of the more advanced changes in the pilot population from 29% to 38%. With no change in the control group rate of 18%, this comparison might have become statistically significant showing an increase in disk degeneration of C₄₋₅.

A summary of the data of Table 3-1 shows that the incidence of some level of disk disease affects the majority of cervical disks, which is expected with the age (late thirties) of these individuals. However it also shows that fighter pilots generally have an increased incidence of degenerative changes of their cervical disks over non-flying controls. Considering that degenerative changes of cervical disks are a common condition with increasing age, these findings can be construed as an acceleration of the normal aging process in the pilot group.

An important consideration regarding this study is that 92% of the pilot group had experienced acute neck pain during exposure to sustained G. Pilots with a history of acute neck pain may be at increased risk for developing degenerative diseases of the cervical spine, therefore must be included in the test group of fighter pilots. As a consequence, the selection of these higher risk pilots as subjects for these types of studies appears to be critical for a survey that has operational relevance. Certainly studies of this sort that do not select pilots that have histories of acute neck injury from exposures to sustained G will have a greatly reduced statistical power in detecting causal effects.

Petren-Mallmin and Linder (99) reported on 16 male fighter pilots with a mean age of 42 years and 2600 flying hours. The control population was 15 age-matched non-flying subjects. They used MRI and the following scoring criteria: (1) disk protrusion was graded (0-3); (2) osteophytes on the posterior border of the vertebra received (0-3); (3) spinal cord compression (0-1); (4) spinal intensity (0-1); (5) disk

Table 3-1: Occurrence of Inter-vertebral Disk Degeneration in Pilots and Non-flying Controls (37).

Disk	All Disk Changes (%) ¹		Mild Disk Changes (%) ²		Moderate Disk Changes (%) ³		P <
	Pilots	Controls	Pilots	Controls	Pilots	Controls	
C ₂₋₃	25	18	0	5	25	14	n.s.
C ₃₋₄	88	64	0	27	88	36	0.01
C ₄₋₅	67	50	29	32	29 (38) ⁴	18	n.s.
C ₅₋₆	79	86	8	36	67	50	n.s.
C ₆₋₇	79	68	13	9	58 (64)	45 (59)	n.s.
Mean	68	57	10	22	53	33	

¹ include mild, moderate, and severe; ² include mild; ³ include moderate; ⁴ in parenthesis includes severe.

height (0-2); and, (6) foraminal stenosis (0-2). Scores for each condition were summed for all of the cervical vertebrae and compared for the two populations.

The mean sum of disk protrusions was 1.8 per pilot and 0.4 for each control subject ($P < 0.05$) and osteophytic scores were 1.8 per pilot and 0.2 for the controls ($P < 0.05$). Other groupings showed increased pathologic effects in pilots that were not statistically significant. Figure 3-1 shows that in the pilot group the mean sum of all of the group scores was highest in C₃₋₄, C₄₋₅, and C₅₋₆. These scores were always greatest in the pilot group for all vertebral levels examined.

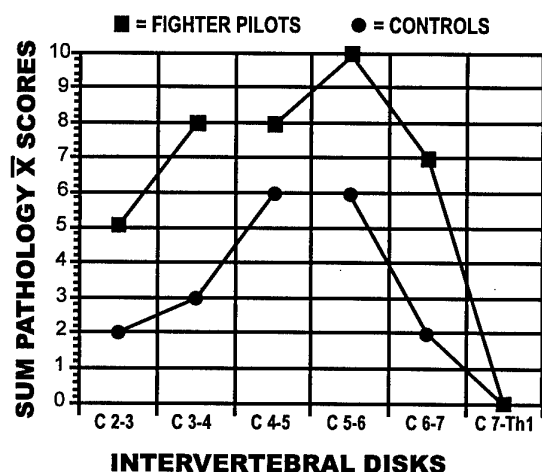


Figure 3-1: Squares identify scores for the fighter pilots and closed circles for the controls.

More information on this study, including a five-year longitudinal study with same pilots, is reported in Chapter 11. Unfortunately this population included only pilots without a history of neck pain. Similarities exist with the changes identified in this study as with those reported by Hamalainen et al. (37) showing that there was increased disk degeneration of C₃₋₄ in the

pilot subject group. The increases in osteophytes and intervertebral disk degeneration were similar and involved the same changes as the vertebrae identified in the Gillen and Raymond (31) study.

Ziyan et al (138) recently reported on a radiographic study of degenerative changes of the cervical spine of 116 active Chinese Fighter Pilots and 62 ground crew controls (Table 3-2). The specific vertebrae involved were not identified. The criteria of degeneration used were: (a) spondylosis; (b) narrowing intervertebral foramen; (c) narrowing of intervertebral spaces; and, (d) physiologic curvature.

Table 3-2. Cervical degenerative changes (%) in pilots and controls (138).

Group	n	Degen ¹		P<
Pilots	116	47.4		0.01 ³
Controls	62	22.6		
Pilots			Neck Pain ⁴	
26-30 yrs ⁵	53	30.2	35.9	0.05 ⁷
31-35	63	61.9	71.4	
600 hrs ⁶	47	27.7	34.0	0.05 ⁸
1000	69	60.9	69.6	

¹ number of subjects; ² % with degenerative change; ³ compared with controls; ⁴ %; ⁵ years of age; ⁶ approximate mean flying hours; ⁷ compared with older pilots; ⁸ compared with longer flying times.

In this study the pilot group had more than a 100% increase in cervical degeneration changes over the non-flying age-matched controls. These degenerative changes increased with age and were directly correlated with increased acute neck pain.

3.3.2 Spinal Canal Stenosis

Hamalainen et al (46) reported on two clinical cases of spinal-canal stenosis of fighter pilots caused by osteophytes. Intervertebral spaces C₆₋₇ and C₅₋₆ showed narrowing of the spinal canal. One case

involved disk prolapse and the other progressive degeneration.

3.4 RELATED OCCUPATIONAL RISK PATHOLOGIES

Makela and Hietaniemi (81) reported a case history of a military parachutist who had neurologic symptoms in the shoulder and fingers. Radiographic examination of the parachutist found degeneration of C_{5-6,7} disks with severe spondylosis. MRI showed disk protrusion. The pain occurred with sudden head flexion during rotation to check for the canopy opening. The authors compared similarities with cervical degeneration found in fighter pilots caused by repeated exposures to high-sustained G.

Petren-Mallmin and Linder (Chapter 11) compare the degenerative change of spondylosis of the cervical spine similar for pilots as found in gymnasts and wrestlers.

Scher (109, 110) found an increased incidence of cervical spine degeneration in rugby players but not in individuals who carried up to 200 pounds bags on their heads many times each day. The latter group did not suffer injury because they maintained a neutral head position.

These observations demonstrate the vulnerability of the neck during head rotation, extension, and flexion that supports the findings of Hamalainen and Vanharanta (34) concerning the increase in % MVC of neck extensor muscles with similar applied forces. Biomechanics of head rotation, extension, and flexion with an increased risk of cervical injury is discussed in Chapter 12.

3.5 SUMMARY AND CONCLUSIONS

These four studies of spinal degeneration have several similarities. They indicate that in a pilot population with a high risk of acute neck injury, there is a significant increase in degenerative changes of the cervical spine. Further, the study of Ziyen et al (138) found a direct correlation between acute neck injury and degenerative changes of the cervical spine. They also reported a direct relationship with age and hours of flying time with spinal degeneration. Unfortunately, age by itself is highly correlated with increased cervical degeneration so the specific effects of flying hours could not be determined.

The key in the investigation of this phenomenon is the selection of a pilot-test group that is at increased risk of cervical degeneration with a history of acute neck injuries from exposures to sustained G. This high-risk group of pilots was used in three of these four studies.

Involvement of the C_{3-4,5} vertebrae, with the development of osteophytes and disk degenerative changes, was a consistent finding. These changes may represent an accelerated aging process of the cervical spine in the fighter pilot population.

CHAPTER 4

DEGENERATIVE CHANGES OF THE SPINE OF FIGHTER PILOTS OF THE ROYAL NETHERLANDS AIR FORCE (RNLAf)^{1,2}

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4.1 INTRODUCTION

The goal of this study was to assess the effects of sustained G exposures of Royal Netherlands Air Force (RNLAf) F-16 pilots on spinal degeneration using X-ray. Specifically we were concerned if accelerated degeneration of the spine occurs as a consequence of flying, is there a statistical relationship with total flying hours and spinal degeneration.

4.2 METHODS

All pilots of the RNLAf had been systematically X-rayed at least twice in the period between 1982 and 1994 with a minimum of two years between radiological examinations. Since this is a retrospective study, these periods of time were not planned and varied considerably (on average 6 yrs between X-rays, Table 4-1). The F-16 group was composed of 188 pilots with an arbitrary selection of a minimum of 150 flying hours in fighter aircraft. The control group was composed of pilots with less than 150 hours of fighter aircraft experience that included 64 helicopter pilots, 63 NF-5 pilots, and 1 F-27 pilot. Data of pilots with prior acute neck injuries from exposures to sustained G were included but not specifically identified.

Because of the higher mean age of the initial X-ray of the F-16 group, which can possibly interfere with the results, statistical analyses were also performed on a subgroup of the total population. A statistical equal mean age was obtained in the subgroup with an initial age between 20 and 30 years. This age-matching resulted in a group of 101 F-16 pilots and 67 pilots in the control group (mean age at initial X-ray respectively of 24.2 years and 23.9 years).

4.2.1 Radiological Examination

Two X-rays of the spine were made of every pilot. Each X-ray consisted of approximately 12 small films

(8 cm²) of frontal and lateral views of the spine with the pilot in a standing position. Two radiologists independently read the films without any knowledge of their origin.

The following classifications were used for the radiological examination:

General: Osteoarthritis/ arthrosis deformans/ spondylosis (Z); scoliosis (S); abnormal alignment (A); and, enchondrosis/ Scheuermann's Disease (E).

Specific: Intervertebral disk degenerative changes/ discopathy (D); osteophytes/ spurring (O); and, osteophytes posterior in spinal canal (P).

The cervical spine used Z, S, and A general classification for all vertebral levels of the cervical region and at each level classification D, O, and P were used.

The thoracic spine used Z, S, and E general classification and at each level classification D, O, and P were used.

The lumbar spine used Z, S, A, and E general classification for all vertebral levels of the lumbar region and at each level classification D, O, and P were used.

Coding used for severity of the abnormalities of the spine follow: 1 = minor; 2 = modest; 3 = moderate; 4 = rather severe; 5 = severe; and, 6 = very severe.

4.2.2 Statistics

Statistical methods used included SPSS 7.5 and SYSTAT 7.0 for all data analyses. Statistical significance levels of $P < 0.05$ and $P < 0.01$ were used. Statistical analyses were performed on the severity scores as on the calculated difference scores between the first and second X-rays.

Table 4-1. Numbers of Subjects Per Group and Group Demographics

Subjects	F-16 Pilots	Controls	P<
Total number of subjects (number of females)	188 (1)	128 (7)	-
Height (cm)	181 (167 - 193) ¹	181 (161 - 191)	n.s. ²
Weight (kg)	75.7 (60 - 98)	74.8 (48 - 100)	n.s.
Time (years) between first and second X-rays	6.1 (2 - 12)	5.8 (2 - 11)	n.s.
Total flying hours	690 (160-1900)	922 (200-2460)	0.01
Age at first X-ray (years)	28.5 (17 - 49)	24.2 (16 - 48)	0.01

¹ Values are mean with range in parenthesis; ² n.s. = not statistically significant (P>0.05)

Statistical analyses were performed to answer the following questions:

1. Is there a difference in population characteristics between the two experimental groups at the start of the study concerning their demographics? Student's t-test was used (Table 4-1).
2. Is there a difference in the severity of disorders between the two experimental groups at the start of the study? Somers' d-test was used with the severity of disorders as the dependent variable. (The reason for this type of test is because of the non-normal distribution with many zeros and only a few deviations, expected frequency per cell was usually less than 5, occasionally zero, and ordinal data with a distinct dependent variable).
3. Are there changes in the severity of disorders in the period between the 2 X-rays, for each separate group? McNemar Symmetry Chi-Square test was used. (The reason for this type of test is that symmetry in the off-diagonal cells in a square table, beware of small cell counts and large samples, and the same amount of columns and rows is needed).
4. Are the changes in time comparable between the two groups? Cochran's Linear Trend test was used. (The rationale for this test is that the significant slope of a regression line, the proportion of F-16 pilots increases linearly across the increasing severity of the difference scores).
5. Is there a difference in level of severity coding between the two radiologists? Cohen's Kappa test was used. (This test was used because of the degree of agreement between the two raters by examination of the proportion of cases on the main diagonal, with 1.0 as perfect agreement, and > 0.4 as reasonable association).

4.3 RESULTS

Since very few pathological changes were found at C₇-Th₁ and Th₁₂-L₁ below the cervical spine, no data comparisons were made at these levels. Pathologies S, A, and E were not presented because a significant relationship with high G was not expected. The results of the spinal pathologies as determined by the two radiologists are shown in Table 4-2. The first 4 questions of this study are identified with question numbers that follow (Table 4-2):

1. Initial differences F-16 group versus the control group;
2. Changes with time in the F-16 group;
3. Changes with time in the control group; and,
4. Differences of change with time of the F-16 group versus the Control group.

The results show several spinal pathologies that were independently identified by the two radiologists. They agree on three major pathologic findings that involved the C₄₋₅ and C₆₋₇ vertebrae showing osteophytic spurring and the cervical spine with arthrosis deformans. In addition, both radiologists found significant pathologies involving C₅₋₆ although their specific diagnoses somewhat differed.

Statistical analysis of inter-rater variability between the two radiologists used Cohen's Kappa Test. Initial X-ray reading agreement found Cohen's Kappa scores of 0.06-0.29. Expressed as percentages, the range of agreement was 61-91%. The difference scores (scores of changes with time) showed Cohen's Kappa scores of 0.01-0.03, which indicates the existence of significant inter-rater variability.

A second analysis of these data of the age-matched group (101 F-16 and 67 control pilots) revealed that most of the initial differences between both groups disappeared. In this selected group, radiologist 1 found a higher degree of osteophytic spurring at C₄₋₅ in the F-16 subjects than in the control group.

Table 4-2: Pathology Classifications of Each Radiologist for the 4 Questions.

Level	Pathology	Question 1 ¹	Question 2 ⁴	Question 3	Question 4
C ₄₋₅	Osteophytic Spurring (O)	>/> ²	0.05/0.05	n.s./n.s. ⁵	F-16 > C ⁶
C ₅₋₆	Discopathy (D)/1 ³	>	0.05	0.05	F-16 > C
C ₅₋₆	Osteophytes Spurring(O)/1	>	0.05	0.05	F-16 > C
C ₅₋₆	Osteophytes Posterior (P)/2	>	0.05	n.s.	F-16 > C
C ₆₋₇	Osteophytes Spurring (O)	=/= ⁷	0.05/0.05	n.s.	F-16 > C
C	Arthrosis Deformans (Z)	>/>	0.05/0.05	n.s./0.05	F-16 > C
L ₃₋₄	Osteophytic Spurring (O)/1	=	0.05	n.s.	F-16 > C
T	Arthrosis Deformans (Z)/2	>	0.05	n.s.	F-16 > C
L _{5-S₁}	Discopathy (D)/1	=	0.05	n.s.	F-16 > C

¹ Questions as numbered in the results; ² Radiologist 1/Radiologist 2 (> greatest in F-16 pilots); ³ /1Radiologist 1 and /2 Radiologist 2; ⁴ P<0.05; ⁵ n.s. P>0.05; ⁶ Changes shown in questions 1-3 are greatest in the F-16 pilots; ⁷ = same for both experimental groups.

Radiologist 2 mentioned a higher degree of arthrosis deformans on general level in the F-16 group compared to the control group.

A correlation coefficient was attempted relating flying hours in the F-16 with the severity of the cervical degeneration using overall and subgroup analyses for age but was not found to be statistically significant. Therefore no correlation between total flying hours and severity of degeneration existed in this study. Also, no consistent relationship was found between changes in severity scores with time and the initial radiological findings.

4.4 DISCUSSION

These findings suggest that frequent exposure to high sustained G might accelerate degeneration of the cervical spine. However several considerations have to be taken into account:

1. There are inconsistencies in reading the radiographical data (relatively poor quality of the radiographs, lack of a uniform classification/coding system, high subjectivity of interpretation);
2. Subject pilot populations were grossly and arbitrarily defined that included many variables that could not be extracted;
3. Age-related degenerative changes interfere because of the higher mean age of the F-16 pilots; and,
5. There are statistical limitations within the design of this study (i.e., many zeros and only a few deviations).

However some assumptions can be made that reduce the significance of some of these problems. For instance, the consistency of the two radiologists agreeing on increased osteophytes on vertebrae C₄₋₅ and C₆₋₇ of F-16 pilots, even though at times they had

high inter-rater variability, indicates that increases in pathologies of F-16 pilots in this study were significant. Also, the results of the age-matched group indicate that a higher degree of degeneration exists in the F-16 group compared to the control group.

The results achieved in this study are in line with those expected. Previous studies have reported that high sustained G might promote degeneration of the cervical spine (31, 37, 99). Gillen and Raymond (31) found degenerative changes in fighter pilots involving disks C₄₋₅ and C₅₋₆ and osteophyte spurring of C₅ and C₆. Hamalainen, et al (37) showed greater disk degenerative changes in fighter pilots being most remarkable in the C₃₋₄ disk. It is also important noting that some (probably the majority) of these pilots had experienced acute neck injury during exposures to sustained G. Petren-Mallmin and Linder (99) reported a combination of degenerative changes greater in fighter pilots involving C₃₋₆.

4.5 SUMMARY

The aim of this study was to examine whether F-16 pilots are at an increased risk of cervical spine degeneration. Retrospectively, all pilots of the RNLAf that were systematically radiographed (at least twice) in the period between 1982 and 1994, were examined. In total, 316 pilots were evaluated, 188 F-16 pilots (mean age 28.5 years at initial X-ray) and 128 pilots in the control group (mean age 24.2 years at initial X-ray). The control group consisted of 64 helicopter pilots, 63 NF-5 pilots and 1 F-27 pilot. These pilots had none or less than 150 hours flying experience with an F-16. Two radiologists, who were blinded as to whether the X-ray films were of F-16 pilots or control group, examined these X-rays separately.

In both groups, the time between the two X-rays was on average 6 years. In these years the control group

had a significantly higher mean amount of flying hours compared to the F-16 group (i.e., 922 against 690 hrs). Though the inter-rater agreement of the X-rays was rather low, both radiologists found comparable statistical significant differences between the two groups, on several levels of the cervical spine. In the F-16 group, an increased osteophytic spurring was found at levels C₄₋₅ and C₆₋₇, and increased arthrosis deformans was found in the cervical spine.

Further analysis of the data of a selection of the total group of pilots, whereby the difference in age between both groups was minimized, showed that the higher mean age of the F-16 pilots was possibly correlated with the increased degeneration in this group. However, both radiologists also found significant degenerative changes in the F-16 group compared to the control group when both groups were age-matched.

No consistent relationship was found between spinal degeneration and initial radiological status. Also, it appeared that increasing levels of spinal degeneration were not related to increasing flight hours.

These findings suggest that frequent exposure to high sustained G might cause premature degeneration of the spine in F-16 pilots. Future research has to demonstrate to what extent age, mission and amount of flying hours have influenced the results.

4.6 RECOMMENDATIONS

The authors recommend the following in order to more fully understand the relationship between exposure to high sustained G and spinal degeneration: (1) the use of spinal screening (MRI or radiograms) for the selection of Air Force Pilots; (2) a uniform international classification and coding system in combination with establishing an international database; and, (3) continue investigation of cervical pathology as it relates to sustained G and include the lumbar spine. The authors also recommend the development and use of special physical conditioning regimens for pilots for improving G tolerances and improving neck muscle strength.

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CHAPTER 5

RADIOLOGICAL EVALUATION OF THE CERVICAL SPINE OF HIGH PERFORMANCE AIRCRAFT PILOTS OF THE SPANISH AIR FORCE (SPAF)

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5.1 INTRODUCTION

Fighter aircraft capable of over 7.5 G and G onset rates of greater than 18 G per s develop significant inertial loads to the anatomical structures of the neck during sustained G exposures (68). This sustained G stressor acts directly on the cervical intervertebral disks, vertebrae, muscles and ligaments (6). Syndromes affecting the cervical spine due to high G forces include a wide variety of symptoms and the involvement of the musculo-skeletal extructures of the neck from muscle and ligament strains and tears, degenerative disk disease and cervical fractures (108).

Conventional radiological methods are not optimum in identifying abnormalities of the intervertebral disk. There is a lack of available data on the occurrence of degenerative changes of the cervical spine of fighter pilots, mostly due to the inadequacies of radiological imaging systems available for selected populations. Magnetic Resonance Imaging (MRI) techniques provide an excellent method for studying intervertebral disks (128) that has very recently been applied in the evaluation of pilots flying high performance aircraft (37, 38, 46). On the other hand, the relation between abnormalities in the spine detected with MRI with or without the presence of symptoms has been controversial. This controversy particularly involves the presense of abnormal findings with MRI in the lumbar spine of people without back pain (62).

The study, reported herein, investigated a population of high performance flyers without prior symptoms of acute neck injury, cervical degenerative disease, nor the presence of abnormalities in the cervical spine, in order to detect pathologies related to repeated exposures to the high G environment.

5.2 METHODS

5.2.1 Subject Selection

A total of 48 male pilots were used in this study. All of them were interviewed to rule out any spine disease or prior spinal trauma. Pilots were eliminated who engaged in sports such as golf, parachute jumping, or gliding that could inflict spinal injuries and those with a history of aircraft ejection. Also none of the pilots in this study had ever experienced neck-related complaints or inflight acute neck pain. Half of these pilots were fighter pilots who currently fly Mirage F-1 or McDonell Douglas F-18. The others were cargo pilots used in the non-G exposed control group. Each group of pilots of high performance aircraft (HPAP) or cargo aircraft (CAP) was subdivided in two groups according to age: (1) ages between 18-31 years and (2) ages 32-45 years. The mean age of the fighter pilots was 32.5 years with a mean flying time of 1272 hours.

5.2.2 Radiological Examinations

Radiological examinations were read and compared independently by two neuroradiologists who did not know the flying status of the population under study. The radiological equipment used for the study and radiological examinations performed were:

1. Conventional cervical radiological examination using General Electric X-ray equipment. Posterior-anterior and lateral examinations were conducted.
2. MRI cervical examination was conducted using General Electric Sigma 1.5 T Superconductive Magnet. Sagittal sections were obtained of the cervical column with 4mm slice thickness and sequences of Spin Echo weighted and Echo Gradient weighted T2.

The following structures were evaluated including the numbers and location of the involved vertebrae:

A. Specific Vertebra: (1) Findings in the vertebral body; (2) Signal intensity; and, (3) Presence of osteophytes.

B. Intervertebral Disk: (1) Signal intensity; (2) Disk height; and, (3) Disk protrusion.

C. Spinal Column: (1) Signal intensity and (2) Deformities.

Radiological signs were evaluated using three grades: 0 = Normal; 1 = Mild; and, 2 = Evident.

5.2.3 Statistical Methods

The statistical method used was U-Mann-Whitney, evaluating the following:

1. Differences between the groups.
2. Differences regarding degenerative changes.
3. Differences between pilots.
4. Descriptive disk findings.

Pearson's correlation coefficient was used to evaluate the results of the two separate readings of the MRI and conventional X-ray findings. The correlation was considered excellent which we attributed to the fact that the same radiology department was used with very similar radiological criteria.

5.3 RESULTS

General data in relation to number of pilots studied, age, flying time and cervical vertebral abnormal findings are described in Table 5-1.

Table 5-1: Pilot demographics and degree of spinal pathologies

Groups	CAP	%	HPAP	%
N ¹	24		24	
Age (yrs)	31.4		32.5	
Flying Time (hrs)	1272		1619	
Signal Intensity ²	0	0	3 ⁵	12.5
Osteophytes	2	12.5	2	12.5
Signal Intensity ³	4	16.6	10	41.7
Disk Height	8	33.3	6	20
Disk protrusion	9	41.3	12	50
Deformities ⁴	1	4.2	1	4.2

¹ Number of subjects per group; ² vertebrae; ³ Disk;

⁴ Spinal column; ⁵ Bold indicate values > in HPA

The most frequently affected disk was C₅₋₆, without significant differences between the fighter pilot and control groups. Vertebral signal intensity was increased in the C₅ and C₆ vertebrae. Vertebrae levels of abnormal findings in the intervertebral disks are shown in Table 5-2.

Table 5-2: Intervertebral Disk Level Abnormal Findings.

Disks	CAP	HPAP
C ₃₋₄	1	1
C ₄₋₅	1	4
C ₅₋₆	9	9
C ₆₋₇	2	2

Table 5-3: Age distribution with the level of disk abnormalities of both groups.

Disk	HPAP ¹	CAP ¹	HPAP ²	CAP ²
C ₃₋₄	1	0	0	1
C ₄₋₅	3	1	1	0
C ₅₋₆	3	3	6	6
C ₆₋₇	0	2	2	0

¹ Age up to 31 years; ² Age between 32-45 years

A statistically significant difference ($P < 0.05$) of the intervertebral disk in the HPAP at the level of C₄₋₅ was found (See Tables 5-2 and 5-3). Also a higher percentage of disk signal intensity was found in HPAP group (58.3%) against 45% in CAP group. The vertebra body signal was significantly greater in the HPAP group against CP ($p < 0.05$) which was more evident in HPA pilots under the age of 31 years.

Table 5-4: Statistical comparison of HPAP with CAP

Variable	Correlation
Vertebral Signal	0.0567 ¹
Osteophytes	1
Disk Signal	0.0536 ¹
Disk Height	0.4562
Disk Protrusion	0.7095
S. C. signal ²	1
S. C. deformity ²	1

¹ Significant $P < 0.05$; ² S.C. = Spinal Column.

A comparison between conventional radiology and MRI regarding grade I disorders showed no significant pathological findings in conventional radiology. Also we

found no correlation between the two types of radiological diagnostic methods. Cases of disk protrusion without decreasing the disk height are not identifiable with conventional radiology but are showed with MRI and no correlation between diagnostic methods was shown.

We found a significant correlation between the two diagnostic methods in grade II lesions where we identified a change in the signal of the disk and a decrease in the height of the disk. Grade III generalized abnormalities showed a clear correlation between MRI and X-ray.

5.4 DISCUSSION

We found a significant increase in prevalence of radiological findings in the cervical spine (intervertebral disk) on MRI examination in asymptomatic HPAP, compared with CAP. The radiological abnormalities were statistically significant at the C_{4-5} level. This vertebral level for disk degenerative changes supports the results of others (31, 37, 60 - Chapter 4, 99). In addition, we found significant pathologies in vertebrae C_5 and C_6 . These results also support the findings of other studies (31, 60, 99).

Our study used conventional radiological methods (X-ray) and correlated those findings with our MRI results. We found a statistically significant correlation between both methods in grade III abnormalities but no correlation in lower grade lesions. This result is not unexpected since improvements in the resolution of MRI techniques of the cervical spine allow more and smaller abnormalities to be detected.

Since we found significant pathological changes in the cervical spine of fighter pilots not having symptoms, we recommend the use of MRI to detect underlying disease of the cervical spine in fighter pilots at the beginning of their flying duties with follow-up examinations periodically, especially if flying high performance aircraft.

5.5 CONCLUSIONS AND RECOMMENDATIONS

Our study found statistically significant increases in the signal intensity of the intervertebral disks C_{4-5} of the fighter pilots over the control subjects. An increase in the signal intensity indicates disk degeneration. We also found statistically significant increases in vertebral intensity signals for C_5 and C_6 that indicates an additional sign of pathological response to long-term high-G exposure.

We recommend the use of MRI to detect underlying disease of the cervical spine in fighter pilots at the beginning of their

flying duties with follow-up examinations periodically if flying high performance aircraft.

¹ The authors thank Dr. F. Esteban and Dr. A. Cuevas who independently read the MRI images and Dr. D. Martinez who contributed to the statistical analyses.

CHAPTER 6

SPINAL INJURY IN TURKISH FIGHTER PILOTS

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6.1 INTRODUCTION

Flight surgeons of the Gulhane Military Medical School, Ankara, Turkey, have recognized a significant incidence of vertebral degeneration of the cervical and lumbar regions, acute cervical spinal injury, and acute neck pain in F-16 aircrew (106). These have been reported in three separate reports that are summarized in this chapter. These findings are discussed in this chapter as they relate to each other and the other information in this TR.

6.2 A COMPARATIVE STUDY OF JET PILOTS' NECK AND BACK DISCOMFORT

A survey was conducted of 214 pilots and 59 non-flying control aircrew. The survey reported on the incidence of back pain that occurred during or immediately after flight. The pain was graded 0-4 with 0 = no pain to 4 = terrible pain. The types of aircraft they fly were also recorded. The results of this survey are shown in Table 6-1.

The incidence of spinal pain was not statistically significantly greater for the F-16 even though pilots noted that they "felt worse" neck and back pain after flying the F-16. In the 1977-1987 time period, 8 pilots were grounded because of spinal problems. The next 10-year period, 48 pilots were grounded with spinal problems that coincided with the introduction of the F-16 into the Turkish Air Force inventory. Within the past 3 years, 75% of pilots grounded were flying F-16 aircraft.

Back pain and total flying hours were directly correlated. The amount of medical days of leave was greater in the pilot population.

6.3 G-INDUCED ACUTE SPINAL INJURY

A retrospective study of all aircrew cases of acute spinal injury was conducted over the period 1987-1997. Of the 82 pilot-cases that had radiological findings, 64.6% were F-16; 12.2 % were F-4; and, 23.2% were F-5. These findings showed 58 (71%) were cervical injuries of which 46 (56%) were at the C₃₋₄ level. The remaining were lumbar or thoracic vertebrae.

Interestingly even though most of the injuries occurred in F-16 pilots, they had the least amount of flying hours; i.e., F-16 pilots had a mean of 980 hrs, F-5 had 1880 hrs, and F-4 had 1610 hrs.

This study shows that G-induced spinal injuries occur in the high-G environment and are directly related to the highest G aircraft (i.e., F-16) flown and not total flying hours. There was no relationship between the use of neck exercises and acute spinal injury.

6.4 VERTEBRAL LESIONS

A prospective study was performed over the time period 1994-1995. All back pain complaints were included and the reported findings are those based on radiological examinations. The jet pilot population had 470 in the group of which 379 were F-4, F-104, T-33, T-37, and T-38. The remaining 91 were F-16 pilots. The results are shown in Table 6-2.

Table 6-1: Survey of pilots and controls (not flying) incidence and severity of neck and spinal discomfort.

Group	Age-yrs	Pain Score (%)					n ¹
		0	1	2	3	4	
Pilots	32.8	43 (20)	102 (48)	45 (21)	20 (9)	4 (2)	214
Control	30.9	38 (64)	11 (19)	9 (15)	1 (2)	0	59

¹ Number per group; Numbers in () are %.

Table 6-2: Incidence and location of acquired vertebral lesions in F-16 and other jet pilots.

Group	n	w/o lesions	w/ lesions ¹	Cervical	Lumbar
F-16	91	52 (57%)	18 (20%)	13 (72%)	5 (28%)
Other	379	220 (58%)	84 (22%)	40 (48%)	44 (52%)

¹ acquired lesions only.

Clearly the incidence (%) of cervical lesions were far greater in the F-16 pilots compared with the other pilot population. The types of lesions identified for the cervical spine included herniated disks, vertebral osteoarthritis and calcification. It was noted that pilots in good physical condition were at lower risk for acquired vertebral lesions during flight.

CHAPTER 7

COMPARATIVE STUDY ON F-1 AND F-15 PILOTS' SPINES BY MRI IN THE JAPANESE AIR SELF DEFENSE FORCE

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7.1 INTRODUCTION

In a previous study from our laboratory, 129 F-15 pilots were surveyed for spinal symptoms. Eighty-nine percent reported muscle pains of the neck during flying. Of the 115 pilots that experienced neck pain, 44 stated that the pain interfered with their flying duties (68). Because of the chronic nature of these symptoms, this study was undertaken to determine if permanent pathologic changes were occurring in the spines of pilots of high performance aircraft.

7.2 METHODS

7.2.1 Subject Selection

Thirty-two F-15 pilots were used in this study with 48 F-1 pilots in the low-G control group. Pilots with previous acute neck injury from sustained G exposures were not excluded from the study. MRI examinations were conducted on the cervical and lumbar spines. In conjunction with this MRI examination, the pilots were surveyed about their spinal symptoms. The MRI used was a MRP 7000, 0.3 Tesla (by Hitachi Corp., Tokyo). Images were made of 5 sagittal sections with T1-weighted, 5 sagittal sections with T2-weighted FS, and axial sections at each disk level with T1-weighted.

7.2.2 Diagnostic Criteria Used for Disk Degeneration

- Grade 0: No Change in signal intensity of disk.
Grade 1: Mild Change: Slight lowering of signal intensity of disk with T2-weighted FS and no annular extension.
Grade 2: Moderate Change: Clear lowering of signal intensity of the disk with T2-weighted FS or annular extension.
Grade 3: Severe Change: Marked lowering of signal intensity of the disk with T2-weighted FS or decrease of disk height or identification of disk bulging with dural contact.

7.3 RESULTS

Age distribution, MRI results, and prevalence of chronic neck pain of the F-15 pilot group are compared with the F-1 (low G) group in Tables 7-1; 7-2; 7-3; 7-4.

Table 7-1: Age and Flying Time (Total Hrs) Distribution of Pilots

Aircraft	N	Age	Age	S.D.	Total Hrs ¹
F-15	19	20-29	25.6	1.9	557 ± 185
	13	≥ 30	31.9	2.1	2200 ± 792
	32	≥ 20	28.2	3.6	1224 ± 952
					425 ± 453 ³
F-1	29	20-29	25.9	2.0	807 ± 548
	19	≥ 30	33.7	2.6	2788 ± 732
	48	≥ 20	29.0	4.4	1591 ± 1146
					1260 ± 1019 ³
Control ²	25	20-29	25.9	2.2	N/A ²
	25	≥ 30	33.6	2.8	N/A

¹ Flying hours in all aircraft (mean ± SD); ² Non-flying controls; ³ Flying hours in current aircraft.

Table 7-2: History of Acute Neck Pain in Flight Associated with G Exposures.

Aircraft	Age Gp yrs	% w/pain ¹
F-15	20-29	31.6
	≥ 30	53.8
F-1	20-29	17.2
	≥ 30	31.6

¹ Mean

The statistical difference of the MRI results between the F-15 and F-1 pilots' cervical spines using Chi-squared Analysis was not significant ($P = 0.08$). Also we found no statistical significant difference with symptoms between pilots of the F-15 and F-1 using Chi-squared Analysis; i.e., cervical spine: not significant ($P = 0.96$). However we found a significant correlation, using

Table 7-3: History of Daily Neck Pain Not Associated with Flying

Aircraft	Age Gp yrs	% w/pain ¹
F-15	20-29	21.1
	≥ 30	53.8
F-1	20-29	20.7
	≥ 30	42.1
Controls ²	20-29	28.0
	≥ 30	44.0

¹ Mean; ² Non-flying

Table 7-4: MRI Results of the Cervical Spine

Aircraft	Age Gp yrs	% Positive MRI ¹
F-15	20-29	31.6
	≥ 30	61.5
F-1	20-29	20.7
	≥ 30	68.4
Controls ²	20-29	44.0
	≥ 30	56.0

¹ Grades 2 and 3 (Mean); ² Non-flying controls

Fisher's Directive Analysis, between MRI findings and symptoms in the cervical spines of F-15 pilots with a $P = 0.03$. In the F-1 pilots, these same correlation's were not significant ($P = 0.06$). We could not find any significant differences between the three groups in terms of flight related pain, daily pain, or MRI data.

7.4 DISCUSSION

The percentage of acute neck pain of the F-15 pilots during flight shown in Table 7-2 is considerably higher than found for the F-1 pilots although less than the 89% reported by Kikukawa et al (68) for F-15 pilots in the Japanese Air Force. Reasons for this apparent discrepancy are that those data of Kikukawa et al (68) were from F-15 pilots reporting on all of their flying experience (including aircraft other than the F-15) and from F-15 pilots older by nearly 5 years. Also her pilots had 657 flying hours in the F-15 whereas the pilots reported herein had only 425 hours (Table 7-1). Acute neck pain in the F-15 pilots was considerably higher (> 50% although not statistically different) than found for the F-1 pilots. However the increase in acute neck pain in the F-15 pilots reported herein over the F-1 pilots is noteworthy since the total hours flown is almost triple in the F-1.

Also in a recent study by Yoshihara et al (136) of Japanese fighter pilot populations, 73.3% F-15 pilots reported flight related neck pain. This population was

75 pilots with a mean age of 32.4 ± 5.9 yrs. Their comparison groups of 64 F-4 pilots reported injuries at 48.4 % (31.7 ± 4.9 yrs of age); 23.4 % for 47 F-1 pilots (29.6 ± 4.5 yrs); and, 3.7 % of 54 cargo pilots (32.5 ± 6.4 yrs). These findings agree with previous reports showing that the incidence of neck pain in lower G aircraft is much less than in higher G aircraft (68, 70, 127).

The lower incidence of acute neck pain in F-15 pilots in this study compare to that reported by Kikukawa et al. (68) and others also may in part be due to the apparent increase in pilot awareness of the hazards of high-G exposures to the neck. We believe that the F-15 pilots in this study used the following precautions to a much greater extent than F-15 pilots in earlier studies: (1) Pre-flight neck warm-ups, (2) Neck muscle strength training, and (3) Avoiding neck movements during G exposures. The acute neck pain in the F-1 pilots in this study is greater (22%) than reported by Kikukawa et al., (68) for F-1 pilots of 15%. This difference is explainable as the F-1 pilots in this study had far greater flying hours than those pilots in the Kikukawa et al (68) study.

What this study does support is the direct relationship of acute neck muscle pain to cervical degenerative changes in only spines in F-15 pilots. It is true that the incidence of degenerative changes of the cervical spine shown in Table 7-4 are not statistically different between pilot populations nor is the incidence of acute neck pain shown in Table 7-2, although twice as great in the F-15 population. Nonetheless, regardless of the differences in the populations of pilots found in this study from other studies, there remains a direct relationship between acute neck pain and degenerative changes of the cervical spine only in the F-15 pilots. Also selection procedures of F-1 pilots are less rigorous than for F-15 pilots; e.g., moderate spinal abnormalities such as spondylosis without pain are acceptable for F-1 pilots but not for F-15 pilots. Therefore in effect we are comparing different populations beginning with "normal" spines that suggest the occurrence of even greater differences between these two experimental groups.

CHAPTER 8

PATHOLOGICAL AND FUNCTIONAL CHANGES OF THE SPINAL COLUMN IN RUSSIAN PILOTS OF HIGH PERFORMANCE AIRCRAFT

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8.1 INTRODUCTION

Exposure of inertial loads on a pilot's spine during high-sustained G flights theoretically may have the following effects:

1. Injuries of vertebrae;
2. Adaptive changes of the structure of vertebrae;
3. Degenerative-dystrophic changes as spinal osteoarthritis; and,
4. Occurrence of a vertebral pain syndrome, associated with vertebral disk degeneration with the development of concomitant functional disturbances in the spine and internal organs.

We will now consider the effects in the order listed above, supporting theoretical research and results of our observations concerning the medical aspects of pilots.

8.2 VERTEBRAL INJURIES

Injury to vertebrae may occur due to forceful compression that exceeds their biomechanical strength. This capability varies widely in individuals, so at certain acceleration levels, there is the risk of spinal injury of pilots (117). The research conducted by us indicate that force-strength quasi-static loading that occurs during exposures to about 9 G can cause spinal injury in about 5% of pilots. Continued flying at high-G levels leads to an increase in the risk of spinal injury.

We classify spinal traumatic lesions as first to second degree levels of severity that show the occurrence of fissures in the vertebral end-plates with herniation of the nucleus pulposus of the intervertebral disk. Such

traumatic lesions are considered by us to be mild and will probably cause only mild symptoms (117).

We did not see these types of injuries in pilots of our fourth generation aircraft exposed to about 9 G. A major reason for not finding this type of injury with exposures to 9 G is that the seat-back angle and the aircraft's angle of attack reduce the level of G acting on the spine. Another reason for the absence of vertebral column fractures in pilots of high performance aircraft may be the result of adaptation of the bone from repeated exposures to high sustained G that results in increased biomechanical strength of the vertebral structure. We have found in pilots of third generation aircraft an increase of mineral density of vertebral body structure by an average of 16% in individuals 40 years of age (83). We also found increased density in the vertebrae of our centrifuge test subjects of 4% after periods of 2 to 2.5 months of high-sustained G studies (118).

8.3 MATHEMATICAL MODEL

We have developed a mathematical model that shows that adaptive restructuring of vertebrae is directly dependent on the duration and levels of G exposures as well as the age of the pilot. This model is composed of a set of linear equations based on chemical kinetics. With this model, we are able to calculate the optimal schedules for training flights on acrobatic maneuvering that provide the best environment for adaptation of the spinal column for pilots of different ages (83). This model also predicts the degree of spinal injury expected with exposures to 12 G. It predicts the level of accumulation of micro-lesions at a value of 0.14, which corresponds to an injury with a severity of the first to second degree. Therefore, for the average pilot

population, exposures to 12 G will not produce dangerous micro-lesions in vertebral bodies. However, these high G levels may be an issue for flyers with relatively low mineral density of their vertebrae.

8.4 SURVEY OF NECK PAIN

We conducted an anonymous survey of pilots of MiG-29 and Su-27 aircraft to investigate the incidence of back pain and level of functional disability. We found that 30% of the pilots reported that they had experienced back pain that involved primarily the neck. Of those, 6.3% were so extremely painful that it reduced their combat readiness and flying safety. These neck pains occur at a G range of 4 to 7.5 G (average of 5.4 G with a duration for 6 s). In all cases, pain occurred with active head movement (check six position) during exposures to G. The increased incidence of neck pain was directly related to the pilot's age, total flying hours and the duration of their flying career.

8.5 RADIOLOGICAL EXAMINATION OF CERVICAL SPINES OF FIGHTER PILOTS

We made clinical and X-ray examinations of the cervical spines of pilots of the MiG-29 and Su-27. This study involved 50 pilots (average age = 36.4 years). Our X-ray examination used panoramic spondylography of the backbone in two projections and Computer Axial Tomography (CAT). In 17 pilots, we found spinal injuries of various degrees of severity that were not correlated with pain during exposures to G. With the use of CAT, we found some forms of protrusions of

intervertebral disks and indications of arthritis of arcospinous articulations with different degrees of severity. These changes may be a response of the connective tissue of the spine to increased mechanical loading with the development of micro-lesions resulting in the development of osteoarthritic spondylosis. Our research suggests that this reaction is an auto-immune type of response of the arcospinous joints that can be diagnosed with the Voll Procedure.

The results of the CAT scan correlated well with our neurological findings. However the relation of the X-ray morphological changes of the cervical spine with pain was not correlated. Therefore we are planning to increase the use of the CAT in the C₄₋₇ region.

8.6 PREVENTION OF SPINAL INJURY

In an attempt to reduce the operational impact of this neck pain problem, the Russian Air Force is doing the following:

1. Research and development of procedures for estimating the biomechanical strength and injury risk in the spine during exposures to high G;
2. Support the pilot with special psychophysiological preparations including specific physical training for strengthening cervical muscles;
3. Reduce the weight of the pilot's anti-G protective garments that involve the head; and,
4. Improve the pilot's working posture with improved seat support.

CHAPTER 9

REVIEW OF THE VERTEBRAL COLUMN PAIN PROBLEMS IN POLISH PILOTS

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9.1 INTRODUCTION

Overload syndrome and back pain are common phenomena, present in contemporary industrial civilizations including modern military aviation. Aircrew members are more often exposed to adverse external factors including in-flight overload with high G, vibration at low frequencies, forced and static body posture and ambient temperature alterations. Head and neck rotation is another risk factor to pilots of high performance aircraft (HPA) during the exposure to high-sustained G

As far as Polish military aviation is concerned, the above mentioned problem became more serious in the 1980s with the introduction of MiG-23 jet fighters. There were numerous cases of pilots (about 42%) complaining of pain in the cervical-humeral region, especially after performing flights at lower altitudes. This problem with cervical spine overload has increased with the use of the MiG-29 high performance aircraft and with pilots performing numerous operational tasks during G.

In an attempt to develop methods to reduce spinal pain, injury, and disease caused by sustained high G exposures a study was undertaken using aerobatic pilots. Aerobatic maneuvers constitute significant G exposures for the pilots ranging from +7.5 G to - 4.5 G. This study was aimed at:

1. Evaluation of +/-Gz acceleration effect on spine function in sports pilots;
2. Evaluation of the effect of the applied physiotherapeutic methods in reducing spine mobility disorders after aerobatic flights; and,

3. Evaluate the application of different physiotherapeutics in preventing spine function disorders.

9.2 METHODS

Spine mobility was examined in 205 military fighter jet and helicopter pilots aged 19-55. The evaluation of spine function in Air Force pilots constituted the basis for performing a study evaluating the effect of +/-Gz on spine function in sports pilots.

Sixty-two male sports pilots aged 21-39 (average - 26.65) volunteered for a study to develop and test methods to reduce the impact of spinal injury. This three-year study used antropometric and spondylometric examinations before and after aerobatic flight. Also after aerobatic flights, pilots were exposed to physiotherapeutic procedures (classical spine massage and Lewit's spine mobilization) to determine their effectiveness in regaining mobility and reducing pain.

For the evaluation of spine mobility, Talar's Universal Spondylogoniometric Set was used. Following the indices of spine mobility, it was measured using a Spinometer: (1) forward and backward head and trunk bending angles; (2) right and left lateral head and trunk bending angles; (3) head and trunk rotation angles; and, (4) parallel forward head movements. Four additional tests were performed for the estimation of total spinal mobility: (1) Schober Test; (2) Otto - Wurm Test; (3) head - knee test; and, (4) fingers to floor test.

Table 9-1: Demographics and mobility measurements of 205 military pilots.

N ¹	Groups	Age (Years)			Kind of Mobility ²		
		Mean	+/- SD	Range	A	B	C
26	Cadets-1 st year.	20.1	0.43	19-22	2.2	31.8	66
22	Cadets-4 th year	23.5	1.0	23-27	5.2	33.3	61.5
29	Junior helicopter pilots	27.1	3.6	23-35	29	30	41
14	Senior helicopter pilots	40.4	3.6	36-47	80	15	5
10	Junior LIM pilots	27.4	3.5	23-35	10	39	51
8	Senior LIM pilots	42.5	5.4	38-55	66	24	10
30	Junior MiG-21 pilots	29.1	3.1	23-35	31	34.5	34.5
10	Senior MiG-21 pilots	42.4	5.9	36-52	78.2	18.2	3.6
19	Junior MiG-23 pilots	29.1	3.3	23-35	37	36	27
7	Senior MiG-23 pilots	37.7	1.4	36-40	77	15.5	7.5
8	MiG-29 pilots	31.4	0.9	30-33	49	42	9
15	Junior SU-22 pilots	31.2	2.2	28-35	53.4	27	19.6
7	Senior SU-22 pilots	39.2	3.7	36-45	56	26	18

¹ Number per group; ² % limited (A), normal (B) and improved (C) global spine mobility

9.3 RESULTS

There is a direct linear relationship with reduction in global spine mobility and age (Figure 9-1). The correlation coefficient for age with limited spine mobility (A, Table 9-1) is $r = 0.96$ with fighter pilots included and 0.93 without the inclusion of fighter pilot data. The spinal limited mobility for the pilots of high performance aircraft is not significantly different from the other groups (Figure 9-1).

The effects of championship aerobic flying on the cervical spine are shown in Table 9-2. Immediately before (M_1), just after the flight (M_2), and 6 hours post-aerobic flight (M_3) antropometric and spondylometric measurements were made of 24 pilots.

9.4 DISCUSSION

Recently, aviation medicine has been particularly concerned with overload syndrome and acute cervical spine injuries in high performance aircraft pilots. Based on our knowledge of the problem, study results and experience in back pain syndrome treatment, we can conclude that:

1. As for lower back pain etiology, we should take into account two main factors, namely - inappropriate body posture during flights and the effect of vibration environment;
2. Cervical spine pain in jet pilots of modern high performance aircraft are caused by rapid onset-rate and high acceleration values that

release inertia forces, often exceeding mechanical endurance of the soft tissue and spinal bone structures. The additional head mass - flying helmet and an asymmetric position of its extra equipment can add to this problem;

3. In order to reduce potential back pain syndrome in pilots, we have to make ergonomic improvements in pilot's seats in the cockpits and pilot's equipment that involves the head (e.g., helmets, masks, goggles-NVG, etc); and,

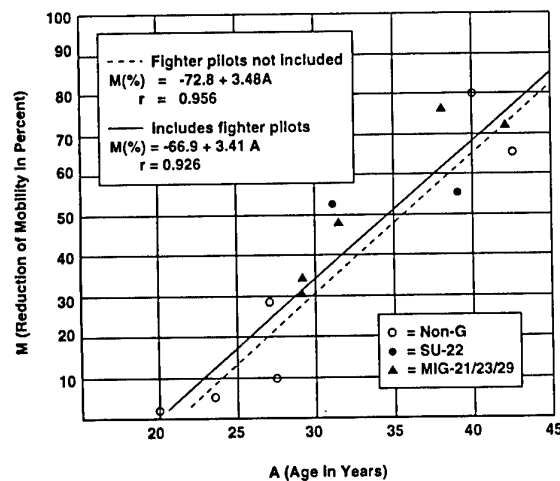


Figure 9-1: The relationship between age and reduction in spinal mobility (A) in pilots of various aircraft is shown (data are from Table 9-1).

Table 9-2: Mobility of the cervical spine and the crown-rump length for aerobatic pilots (n = 24).

Indices	M ₁	M ₂	M ₂ -M ₁	%	M ₃
Forward head bending angle	54.5	46.3	-8.2	15.05	55.6
Backward head bending angle	62.8	56.6	-6.2	9.87	61.8
Right lateral head bending angle	38.9	33.9	-5	12.85	38.0
Left lateral head bending angle	38.9	33.3	-5.60	14.40	38.5
Positive (R) head rotation angle	80.6	72.4	-8.2	10.17	80.5
Negative (L) head rotation angle	81.3	73.9	-7.4	9.10	81.1
Parallel forward head movement (cm)	6.6	5.6	-1	15.15	6.5
Crown-rump length (cm)	91.43	89.60	-1.83	2.00	90.99

4. Methods of selection of candidates to aviation have to be improved with particular attention paid to high performance aircraft pilots.

Talar (119) evaluated spine function in military pilots and found that spine mobility becomes significantly limited in pilots over 35. Most affected were the cervical and lumbar spines in the frontal plane. As far as aircraft types are concerned, spine mobility limitation affects most often senior MiG-21, MiG-23 and SU-22 pilots and junior MiG-29 pilots. Table 9-1 shows the percentage of pilots flying different aircraft with limited, normal and improved global spine mobility. Analysis of these data finds that age plays the primary role in reducing spinal mobility in all pilots regardless of their aircraft. There is some indication that is greater in pilots of high performance aircraft but this difference is not statistically significant.

In Poland, spine overload syndrome has been studied for a long time at the Polish Air Force Institute of Aviation Medicine (PAFIAM). These studies include mainly the diagnostics, treatment and aeromedical certification, periodic and occasional examination as well as sanatorium and hospital treatment. Apart from neuroses, back-pain syndrome is the most common disease that occurs in aircrew. Therefore, it constitutes a serious clinical and certification problem.

The analysis made in the summer periods 1981-90 at the Psycho-neurological Institute, PAFIAM, showed that pain in the thoraco-lumbar spine is the reason for hospital admissions in about 1/3 of the aircrew. The results of another study performed at PAFIAM in 1995-96, showed an increase in back pain that constituted 50% of all hospitalized cases. The pain was chiefly located in the lumbar spine (27% of the cases treated at the hospital) and cervical spine (15%). In 1992-1997 spinal diseases constituted 14% of all direct reasons of considering air force pilots unfit for air service. In the

aviators who were considered unfit (n = 101), spine disorders occurred as coexisting ailments.

Pilots performing aerobatic flights are exposed to substantial stato-dynamic spine overload. The examination of cervical spine mobility, immediately following a 10 min aerobatic flight, showed significant limitation of mobility range compared to the initial pre-flight examination (Table 9-2). Such a limitation in spine mobility may result from protective tension of paraspinal muscles and from the changes that occur in the intervertebral disk.

The measurement of crown-rump length revealed a significant reduction, which is most probably due to intervertebral disk height lowering. The observed post-flight reduction of crown-rump length in pilots after the aerobatic flight was above 1.83 cm. The decrease in intervertebral disks height affects a change in spinal mobility as the surface of adjacent vertebral shafts remains constant, the nucleus pulposus is the only changeable element.

Recovery time of reduced spine mobility due to an aerobatic flight was measured 6 hours post-flight. It was shown that in most cases, spine mobility increased significantly from the values obtained immediately after the aerobatic flight, but the previous mobility was not as yet complete.

The effectiveness of classical spine massage and mobilization according to Levit, in reducing spine mobility disorders after aerobatic flights was measured and found to be statistically insignificant. These findings and the overall analysis of spine mobility and crown-rump length may confirm the role of intervertebral disks in maintaining spine mobility. However one can state that massage causes a reduction of reflex paraspinal muscle tension due to in-flight exposure to acceleration forces.

We found that the use of physiotherapeutic measures significantly accelerated the recovery of spine mobility and decreased the muscle tension. The authors suggest the necessity of designing and adapting a special, complex program of prophylactic undertakings in order to prevent the problems of spinal overload syndrome among aerobatic pilots. Pilots should also be properly informed about the problems of aerobatic and/or jet combat maneuvers on spine mobility and the methods available for reducing spine overload injuries.

9.5 PROPHYLAXIS AND TREATMENT SYSTEMS DEVELOPMENT

Our history on this topic finds that from 1992 - 1997 spinal disorders account for 15% of disabilities related to air service. Back pain is extremely common among fighter pilots with 50% of our pilots complaining about transient pain of the cervical and lumbar spines. During 1994 - 1997, 52 pilots were hospitalized from spinal injury and in the first half of 1998, 6 pilots have been hospitalized with 'Cervical Spine Pain Syndrome'. Because of our concerns about spinal injury of fighter pilots, we have developed a 'Back Pain Syndrome Monitoring System' for Air Force Pilots.

We are so concerned about this problem that we have established aggressive measures in combating spinal injury of fighter pilots that include pilot candidate selection criteria, pilot monitoring system, and multifaceted treatment regimens.

In October 1997 we formed a team of medical specialists on back pain of pilots to gather information on this topic, consult, analyze data, initiate research, and develop prophylaxis measures. Our initial efforts involved increased specialist training for flight surgeons and awareness and prophylaxis training of our fighter pilots. We have implemented the following selection criteria for our Air Force Cadets. The following conditions disqualify personnel from becoming pilots: (1) extra cervical ribs; (2) vertebral blocks, congenital semi-vertebrae; (3) spinal curvature; (4) spondylolisthesis; (5) prolapsed spinal disk; (6) Scheuermann's Disease; and, (7) anomalies in L-S Junctions (Ferguson's Angle to 35°).

Methods for the examination of pilot candidates include: (1) anthropometric measurements; (2) spinal mobility; (3) full spinal radiogram; and (4) medical history.

Treatment of pilots with this pain syndrome is very aggressive beginning within 7 days of the diagnosis. Treatment includes various therapies, rehabilitation, sanatorium care, and surgery. Treatments are provided for a maximum of 6 months. If pain persists, the pilot is moved to multi-crew aircraft that do not have ejection seats.

9.6 CONCLUSIONS

Spine mobility limitations are primarily related to increasing age. However it becomes more limited in older Air Force pilots. Most affected are the cervical and thoraco-lumbar spines in the frontal plane. Spine mobility becomes most limited in senior MiG-21, MiG-23 and SU-22 jet pilots and junior MiG-29 pilots. Helicopter pilots as compared to jet pilots have their thoraco-lumbar spine mobility more limited and the changes are more advanced in older pilots. Variable \pm Gz acceleration values occurring in aerobatic cause substantial restriction of cervical spinal mobility in sports pilots. The application of post-flight physiotherapeutic measures reduces the effect of spinal functional disorders. The application of therapeutic techniques in pilots before an aerobatic flight is justified and useful in the prevention of functional spine disorders and should be considered routine for military fighter pilots.

9.7 RECOMMENDATIONS

Based on our studies, experience, and the available literature, it seems prudent to support pilot's performance with the application of special physical exercises and comprehensive prophylactic program. These should include:

1. Appropriate rest (e.g., relief postures for the lumbar and cervical spines), proper diet and weight control;
2. Regular strength and aerobic training with stretching and functional respiration training;
3. Massage, sauna and physiotherapy session during weekly activities;
4. Physiotherapy before and after aerobatics flight mission and air combat maneuvers; and,
5. A physical warm-up including stretching neck muscles immediately before taking off while the pilot is in the cockpit.

CHAPTER 10

CERVICAL INJURY AND DEGENERATION IN THE FINNISH AIR FORCE

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10.1 INTRODUCTION

In Finland we have been studying the issue of fighter pilots' neck injuries since 1987, when our pilots started gradually complaining of 'Hawk Neck'; i.e., in-flight neck pain when doing aerial combat maneuvering (ACM) with a Hawk Jet Trainer. Other fighter aircraft, such as MiG 21 or Draken, did not present a great problem. The Hawk was introduced to flight training in 1981 but several years lapsed before pilots began to complain about neck injury. This delay was attributed to either the pilots' fear of reporting in-flight neck pain because of possible grounding or perhaps the pain was coming from degenerative changes of the cervical spine that had required several years to develop.

In response to these complaints from pilots about neck pain, we developed a long-term research program that would systematically develop information to address the problem. That program resulted in several research studies and publications that have provided some understanding of the problems of neck pain in Finnish Fighter Pilots. A brief description of those studies and the referenced publications follow in chronological order:

1. The occurrence of acute neck injury and other neck and shoulder disorders among fighter pilots frequently exposed to high sustained G, and the relevant circumstances at the onset of acute neck injury (5);
2. The strain on the *cervical erector spinae* muscles under high G and the effect of head movements on that strain (34, 74);
3. The strain on the *cervical erector spinae* muscles when wearing flight helmets of different weights (33);

4. Relationship of frequent exposures to high G to premature degenerative changes in the cervical intervertebral disks (37);
5. Subject-related factors of acute neck injury (35, 36);
6. Vertebral disk compression from high sustained G during aerial combat maneuvering exercises (39);
7. Quantification of muscular strain during ACM exercises (93);
8. Quantification of muscle fatigue during repeated ACM (94);
9. Dose-response relationship between G exposure and degenerative changes in the fighter pilots' cervical and lumbar spines (42);
10. The effect of neck training (43) and general muscle strength training (44) on fighter pilots' acute neck injuries; and,
11. The occurrence of work-related thoracolumbar pain among fighter pilots (45).

In conjunction with these publications of the planned study protocols, we have published reports of clinical cases on cervical disk bulges (38) and G induced stenosis of the spinal canal among fighter pilots (46). Some of our results can be found in two review articles (41, 47), the former being the doctoral thesis of Dr. Hamalainen. An incidental isolated event of interest will also be reported, that involved the EMG-recording of the muscular reaction of the lateral neck muscles during an acute in-flight neck injury during an ACM. The muscular strain in the neck muscles exceeded the 100% MVC (257 % MVC) that resulted in an injury that terminated the flight (93). Recently we have studied the pain thresholds of pilots with and without acute neck injuries (65).

10.2. METHODS

Experienced fighter pilots and student fighter pilots of the Finnish Air Force have participated in these studies. Some studies used age-sex matched control subjects.

Methods that were used depended upon the subject of the research; i.e., surface Inflight EMG (IEMG) recordings, magnetic resonance imaging (MRI), subjective surveys involving questionnaires, physical examinations (neck strength measurements, cervical range of motion, grip strength and anthropometric measurements), and bicycle ergometry combined with cold pain sensitivity test.

10.2.1 The Development of a Reliable-Simple Method for Measuring Isometric Neck Muscle Force.

This method was developed and validated for our research on neck muscle tensing of pilots during exposures to high-sustained G. We found other methods not suitable for our purposes. The reliability coefficients of our method were 0.74 – 0.80 that proved adequate for our research program.

10.3. RESULTS

A brief description of the results of each major study is described in this section in the chronological order that the studies were conducted.

10.3.1 Survey of Neck Pain Among Finnish Military Pilots.

Forty-eight percent of the Finnish military pilots had experienced acute in-flight neck injury at least once during their flight career. Other neck and shoulder disorders had occurred in 28% of the pilots, most of them (85%) being flight instructors or otherwise experienced pilots. At the onset of acute neck injury the position of the head was twisted in 98% of cases. Acute in-flight neck injury (pain) never occurred below 4 G. The occurrence of acute pain was most common in the Hawk MK 51, an 8 G aircraft. Only a few acute neck injuries occurred in the MiG 21 and Draken.

10.3.2 Effect of Sustained G and Head Movements on Cervical Erector Spinae Muscle Strain. An in-flight IEMG-study.

Muscular strain increased in neck extensor muscles with increasing G and head movements. At 7 G the muscular strain was 5.9-fold (i.e., 37.9% maximal voluntary

contraction, % MVC) compared with 1 G. In some pilots, the muscular tolerance (100% MVC) was ipsilaterally that was reached before 4G with the head rotated or flexed. Fighter pilots are most susceptible to acute in-flight neck injury when the strength of the neck muscles is insufficient to support the head during G.

10.3.3 Effect of Flight Helmet Weight and G Forces on Neck Muscle Strain. An in-flight IEMG-study.

The study indicated that a lighter flight helmet may cause less strain on neck structures than a heavier one. The positive effect of helmet weight was seen only under high G. Changing from a heavier (1940 g) to a lighter (1310 g) helmet reduced the mean muscular strain from 9.5 to 8.8% MVC and from 20.2 to 17.1% MVC under 4 and 7 G, respectively. Thus only some acute in-flight neck injuries will be avoided by using lighter flight helmets. However in higher-G aircraft, this helmet effect would probably be more pronounced.

10.3.4 Degeneration of Cervical Intervertebral Disks in Fighter Pilots. A MRI-study.

Both the occurrence and the median degree of disk degeneration in each cervical disk space were greater among the pilots than controls that were matched for age and sex. However these differences were statistically significant only in the C₃₋₄ space.

10.3.5 Determinants of G-Related Neck Pain. A preliminary survey including physical examinations.

The number of flight hours, level of work strain, job satisfaction, symptoms suggesting psychological distress, smoking habits, and frequency of physical training (i.e. muscle strength, muscle endurance, and aerobics) were obtained with a questionnaire. A physical examination comprised of the subjects' height, body weight, body mass index (BMI), head and neck circumference, passive-cervical range of motion, grip strength, and isometric strength of neck muscles.

This cross-sectional study found that general muscle endurance-resistance training could prevent acute in-flight neck injuries. The subjects (n = 27) did not do any specific neck training.

10.3.6 +Gz-Related Neck Pain: A Follow-up study. A questionnaire study.

The study consisted of the same questionnaire and physical examination used in the study reviewed

immediately above (10.3.5). The number of subjects was 66, and the follow-up time period was 1 – 3 years. This study did not confirm the results of the cross-sectional study, which suggested that general muscle endurance training should prevent acute in-flight neck injuries. The cumulative incidence of acute in-flight neck injury was 37.9%, and the aircraft flown was Hawk MK 51. The number of G-flight hours, of the same age pilots, was the only significant determinant of acute in-flight neck injury.

10.3.7 Spinal Shrinkage Due to +Gz Forces. A study on strain in spinal column caused by G using height measurements.

Aerial Combat Maneuvering with a Hawk Jet Trainer with high sustained G for 40 minutes caused a 4.9 mm decrease in body height indicating that high G strains the spinal column. This G stress is equal to standing with a barbell of 10 kg on shoulders for 20 minutes. Recumbent rest before G-flights increased body height by 2.5 – 3.5 mm thus providing the intervertebral disks increased capability to absorb G stress during flights.

10.3.8 Quantification of Muscle Strain During Aerial Combat Maneuvering Exercise. An in-flight IEMG-study.

The study measured in-flight muscular strain (% MVC) in thigh, abdomen, back and lateral neck muscles during ACM. The mean muscular strain was 5.2 – 19.8% MVC with the lateral neck muscles having the highest % MVC. Peak muscular strain over 50% MVC occurred mostly in the lateral neck muscles during ACM. The highest peak strain (257% MVC) was measured in the lateral neck during ACM that occurred with an acute neck injury. This painful episode caused discontinuation of the flight.

10.3.9 Muscle Fatigue Caused by Repeated Aerial Combat Maneuvering Exercises. An in-flight IEMG-study.

In this study, aerial combat maneuvering exercises with a Hawk Jet Trainer were repeated 3 times during the same day. These maneuvers caused a significant decrease in muscle strength and an increase in muscular fatigue in neck extensor and lateral neck muscles, but did not affect the back or abdominal muscles.

10.3.10 G Dose – Degenerative Change Response Relationship in Fighter Pilots' Cervical and Lumbar

Spines. A 5-year follow-up on-going MRI-study with non-G-exposed controls.

Cervical and lumbar spines of student fighter pilots and controls were examined by MRI prior to the pilots' exposure to G and 5 years later. Preliminary analysis in 12 subjects suggests that the lumbar spine was not affected. Data analysis has not been completed on the cervical spine. This study with spine examinations at regular intervals will be continued for several more years.

10.3.11 Relationship Between G Exposure and Neck Physical Training. A Preliminary Study. A questionnaire study with physical examinations involving specific neck training.

This study suggested that neck training might prevent acute in-flight neck injuries. The subjects trained regularly during a period of one year after having had an intensive period of neck training guided by a physiotherapist. However the results must be considered inconclusive since a control group was not included.

10.3.12 Neck Exercises and General Muscle Strength Training in Prevention of Acute In-Flight Neck Injuries.

This study included an education program "neck school" that was given to student fighter pilots (n = 52) by a physiotherapist. This training included four weeks of intensive neck endurance training with follow-on recommendations for weekly neck-endurance training using a rubber sling, and pre- and post-flight neck muscle stretching exercise ('self-prevention'). This program was then followed voluntarily by the pilots. Unfortunately it did not reduce the incidence of acute in-flight neck injuries during a period of 1–3 years. However the voluntary compliance of the pilots to this program was quite variable, such that its effectiveness was not tested properly. On the other hand, the vast majority of these pilots were involved in a regular weight-lifting program and they had fewer neck injuries.

10.3.13 Thoracolumbar Pain Among Fighter Pilots. A questionnaire study.

In this study, 320 fighter pilots, and 283 controls, matched for age and sex, were asked about the occurrence of thoracic or lumbar spine pain during the last twelve months. Fighter pilots had experienced thoracic pain 2.3 (1.5 – 3.5) times more often than the controls during the previous twelve months.

Among the pilots, the occurrence of thoracic pain was directly correlated with flight hours with a risk factor of 26.9 for the most experienced pilots. Logistic regression analysis revealed that age was not a factor in experiencing thoracic spine pain. There was no difference between the pilots and controls with respect to experiencing lumbar pain during the preceding twelve months. But during their career, fighter pilots had experienced pain more often than controls with a risk factor of 1.8 (1.3 – 2.6).

10.3.14 Cervical Disk Bulges in Fighter Pilots. A MRI study.

This clinical study consisted of three clinical cases of bulging cervical intervertebral disks in fighter pilots, who experienced acute in-flight neck pain during high-G ACM. One of the pilots had surgery to correct severe neurological symptoms and the other two were treated without surgical intervention.

10.3.15 G Associated Stenosis of the Cervical Spinal Canal in Fighter Pilots. A MRI study.

This study suggests that repeated exposure to high-sustained G can cause degenerative narrowing of the spinal canal caused by the formation of osteophytes. This narrowing can produce severe neurological symptoms. One case required surgery because of severe neurological symptoms in all four extremities. The diagnosis was made using MRI and was thus verified by surgical intervention. This case was purely degenerative. The other case of stenosis was complicated by a bulging cervical disk and a congenitally narrow spinal canal.

10.3.16 Fighter Pilots' Neck Pain. Author's academic dissertation.

The thesis comprises six original studies of 35 pages with a thorough presentation on the subject of cervical injury and degeneration and related pathologies of 76 pages.

10.3.17 Neck Pain in Fighter Pilots (Nackenschmerzen bei Jagdfliegern)

A review of some of these studies on cervical injury and degeneration.

10.3.18 Effects of Physical Exercise on Cold Pain Sensitivity in Fighter Pilots With and Without a History of Acute In-Flight Neck Pain.

Physical exercise increased pain thresholds ($p < 0.001$) in pilots with a history of acute in-flight neck injury, but not in the control group. Exercise induced a significant decrease in pain responses to supra-threshold stimulation in both groups. The exercise effect was more marked both in pain intensity ($p < 0.05$) and unpleasantness responses ($p < 0.01$) in pilots with a history of acute in-flight neck injury. Moreover, exercise more markedly ($p < 0.05$) decreased the unpleasantness feeling over pain intensity in both groups of pilots.

The study suggests that there could be differences in intrinsic analgesia mechanisms or that these mechanisms are acting differently in subjects with and without episodes of pain. This finding may partially explain why some fighter pilots experience acute in-flight neck injuries and others exposed to the same environments do not have neck pain.

10.4 DISCUSSION

The published information presented in this chapter has been integrated into Chapters 1, 2, 3, and 12 as referenced material in this TR. It should be remembered that these studies were included in a comprehensive research program that was devised to understand the problems of neck injury and degeneration in Finnish Fighter Pilots flying high performance fighter aircraft with 8 G capabilities. Finland now has F-18 aircraft that are flown routinely at 7.5 G thus the occupational risk associated with high-sustained G should not increase in these fighter pilots. The information developed in this program is applicable to all high G aircraft.

It is important to remember that cervical spine injury and degeneration is a multifactorial and complex problem. Therefore solutions to these problems will be difficult requiring additional research. It is clear that individual pilot susceptibility to cervical pathologies varies significantly. Therefore there are valid reasons for selecting pilots who are resistant to this problem. However more research will be required to determine the optimum pilot-selection criteria for the cervical spine in selecting fighter pilots.

10.5 CONCLUSIONS

The information developed from the research program described herein has resulted in the following conclusions:

- Fighter pilots' neck injuries are common and directly correlated with the level and duration of the G exposure.
- The basic scenario for experiencing in-flight acute neck injury involves a minimum inertial force of 4 G with the risk of injury increased with neck/head positioning that involves a combination of rotation and/or flexion/extension during ACM.
- G-induced stress during an ACM affects the entire spine and often exceeds the physical capability of the spinal column. Apart from acute injuries, such as prolapsed cervical intervertebral disks and fractures of the vertebral body, frequent exposures to high-sustained G can increase the normal aging process of cervical spinal degeneration. This degeneration process has been associated with narrowing of the spinal canal (e.g., spinal stenosis from spondylosis).
- Lighter-weight flight helmets will reduce physical strain on cervical structures but will have limited value in preventing acute neck injuries.
- The only identified individual risk factor for acute in-flight neck injury that is statistically significant is the number of G flight hours.
- General muscle strengthening and neck training may be beneficial in preventing neck injury and increasing the pain threshold in fighter pilots.

10.6 RECOMMENDATIONS

From the results and conclusions described herein, the authors propose the following recommendations for the Finnish Air Force:

- Fighter pilots should avoid moving their head during sustained G exposures. They should understand that they are at increased risk for injury with their head rotated, flexed, and/or extended during ACM especially at levels ≥ 4 G.

- Fighter pilots should avoid onsets of G that are unexpected by their copilots thus allowing time for muscle contractions that help protect the neck.
- Fighter pilots should regularly perform general muscle strengthening exercises that include neck muscles. The exercise program used in the Finnish Air Force is available on a CD-ROM 'The Finnish Air Force Physical Education Team' that is available in Finnish, English and Swedish languages.
- Perform routine pre- and post-flight stretching (warmup) of neck and shoulder muscles.
- Recumbent rest for 20-30 minutes before and after G flights to increase intervertebral disk height and regain the water content of the intervertebral disks of the entire spine that is lost during G exposures.
- Flight helmets should be 'lightweight' using optimum integration concepts of life support equipment to reduce moment forces.
- Ergonomics of the cockpit of fighter aircraft should provide maximum support and optimum positioning of the head, neck and body.
- Mechanical devices should be developed to protect the neck during increased G maneuvers.
- Cervical spines of fighter pilots should be examined regularly using MRI Methods.
 - A MRI of the cervical spine at the beginning of flight training; and,
 - Follow-on MRIs of the cervical spine at five, eight, eleven, and fourteen years of active high-G flying. Additional MRIs will be made at regular periods, to be determined, if the pilot continues to fly beyond 14 years.

CHAPTER 11

CERVICAL SPINE DEGENERATION OF FIGHTER PILOTS OF THE SWEDISH AIR FORCE*

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11.1 INTRODUCTION

The mean flying hours for the Swedish Air Force for each pilot are 100-250 hrs annually. Younger pilots will have the most flying time. High G-loads (i.e., 7- 9G) are common in modern high performance aircraft. In addition, the positioning of the pilot in the ejection seat is very static and the harness restraint limits the pilot's mobility. These restrictions require that most of the motion of the pilot has to be performed in neck region. Certain head-neck motions are required to target-track during aerial combat maneuvers (ACM) often resulting in vigorous rotation and extension of the neck especially in 3-6-9 o'clock positions. It is known that tolerance of the spine for axial load is relatively high, yet much lower when the load on the spine is in other directions (Chapter 12; 49, 59, 109, 110). A study of the biomechanical load on the neck in the C₇ region has shown that with a helmet device and the neck flexed 40°, a 7 G-turn will require a nearly maximal muscle force contraction in a normal male population to counteract the induced G load (54).

Several studies have shown that acute neck injuries that result in muscle soreness commonly occur in high performance fighter pilots (36, 68, 92). Acute injuries involving vertebral fractures, rupture of ligaments or cervical disk herniations have been reported in conjunction with exposures to rapid onset of sustained G but are less common (6, 108). Thus, the cervical spine of a fighter pilot is exposed to extreme external loads with the head in various positions that may result in spinal degeneration changes.

Not surprisingly spinal degeneration found in fighter pilots is similar to spondylosis of the spine as found in gymnasts and wrestlers. Also early onset of cervical degeneration has been described in rugby players (109) and significant degenerative findings are reported following prolonged athletic activities without clinical symptoms. These findings are regarded as similar to degenerative findings in other asymptomatic populations.

MRI is a very sensitive imaging technique found to be quite useful for the spine and soft tissues. It is not invasive and does not expose the patient to radiation. The purpose of the present study was to determine if repeated sustained G loads from flying high performance aircraft were associated with spinal abnormalities using MRI techniques. MRI examination of the cervical spine was performed on two groups of Swedish Air Force (AF) pilots and one group of age-control non-flying subjects (C). The members of one group of AF pilots (Experienced Pilots; EP) were approximately 18 years older with ten times more flying hours experience than the (Young Pilots; YP) group. These pilots did not have symptoms related to injury of the cervical spine. Since degeneration of the spine is known to occur with increasing age, this study included an age-matched asymptomatic control group (C) that had not been exposed to sustained increased G.

This longitudinal study was a repeat, 5 years later, of an earlier study using the same subjects (99). Fourteen of the 16 EP group, 13 of the 14 C group and all of the YP returned for the 5 year follow-up study (Table 11-1).

11.2 METHODS

The initial study group of experienced pilots (EP) consisted of 16 male air force pilots mean age 41.6 ± 6.8 (28-49 yrs), with a mean accumulated flying time of 2600 hrs (1500-4600 hrs) was examined with MRI. None of them had any cervical spine complaints. The control group (C) without any exposure to high G was composed of 15 male volunteers, mean age 42.1 ± 5.8 (32-48 yrs). These age-controls were recruited among hospital and aircraft industry employees. Only persons without symptoms of the cervical spine were included. A third group of 13 young air force pilots (YP), age 23.1 (21-26 yrs) each with an accumulated flying time of 220 hours was included in this study.

The age and flying-hours experience of the three groups for the 5-year follow-on study are shown in Table 11-1. The EP group had increased their mean total flying hours from 2600 to 3100 hrs and the YP pilots experience in flying high G maneuvers had increased even more going from only 220 to 915 hrs of mean total flying time.

11.2.1 MRI Technique

MRI examinations were made with a 0.5 T superconducting magnet (Siemens Magnetom) using a head coil. All persons were examined in the supine position. Sagittal spin-echo T_1 -weighted 500/30 (TR/TE), and T_2 -weighted 1500/30.90 images were obtained by using 5-mm-thick slices with a 20% gap between consecutive sections. A sagittal GMR sequence (FL 20, Flash 2D) with a thickness of 9 mm was also recorded. Two acquisitions were used for TR 500 ms and one for TR 1500 ms. Eleven axial slices (TR/TE 500/30) with a thickness of 7 mm were spread to cover the whole cervical spine primarily for the purpose of measuring certain muscles (79) and not for the analysis concerning degenerative lesions; however, they were also of some value in the present study.

Follow-up MRI was performed with 1.5T or 0.5T superconducting magnets (Philips ACS or T5) using a head coil. All persons were again examined in the supine position. Sagittal T_1 -weighted and T_2 -weighted spin-echo images with a thickness of 3 mm and a 10% gap were recorded. When degenerative lesions were found, axial T_2 -weighted images were also recorded covering the affected (involved) segments.

11.2.2 MRI Evaluation

The MRIs were read by a radiologist who is a musculoskeletal MRI specialist, without subject identification. The grading criteria that were used follow:

- Disk protrusions/herniations were graded from 0 to 4 on the sagittal image.
 - Grade 0 represented a straight contour of the posterior annulus fibrosus in line with the posterior walls of the adjacent vertebral bodies.
 - Grade 1 was a small protrusion occupying less than half the anterior subarachnoid space.
 - Grade 2 was a medium size disk protrusion interfering with $> 50\%$ and $< 100\%$ of the anterior subarachnoid space.
 - Grade 3 indicated a disk reaching the cord without evidence of cord compression.
 - Grade 4 meant compression of the spinal cord.
- Osteophytes on the posterior borders of vertebral bodies were graded using the same 0 – 4 scores.
- Cord compression was graded as non-existent or present, graded 0 or 1, respectively.
- Signal intensity (SI) in each disk was graded 0 or 1 from the T_2 weighted and flash images; 0 meant normal, i.e., intermediate to rather high SI, equivalent to other, otherwise normal appearing disks; 1 meant reduced SI that is believed to be reflecting dehydration in the disk.
- Disk height was compared with the above disk or, if that was obviously abnormal, compared with the nearest disk that appeared "normal". Disk height was graded 0-2; 0 meant no or $< 25\%$ reduction, 1 was 25-50% reduction and 2 meant $> 50\%$ reduction.
- Foraminal stenosis due to degenerative arthritis in an intervertebral and/or uncovertebral joint with skeletal hypertrophy was graded 1 when unilateral, and 2 when bilateral lesions were found. In grade 0 no foraminal stenosis was found.

Each spinal evaluation criterion (shown above) for each experimental group was compared between groups using the total sum of the grades at each disk level and for the total cervical spine (C_2 to Th_1); i.e., scores of all of the subjects per group were summed (Σ) for each evaluation criterion.

Table 11-1: Sum of scores of the cervical spine degeneration criteria for each experimental group.

Group	EP (O)	EP (5 yr) ²	C (O)	C (5 yr) ²	YP (O)	YP (5 yr) ²
Subjects per Group (n)	16	14	15	14	13	13
Mean age	42 (28-49)	47 (35-54)	42 (32-48)	47 (37-52)	23 (21-26)	28 (26-30)
Flying hours ¹	2600	3100	0	0	220	915
Osteophytes ¹	2.6 (0-13)	4.7 (0-11)	0.7 (0-3) *	3.0 (0-7)++	0.3 (0-2)	0.6 (0-3)++
Disk Prot/herniation ¹	3.4 (0-11)	6.4 (0-16)*	1.2 (0-5) *	4.9 (0-10)++	0.4 (0-3)	1.3 (0-5)++
Cord Compression ¹	0.4 (0-2)	0.6 (0-3)	0 *	0.3 (0-2)	0	0
Foraminal Stenosis ¹	0.6 (0-4)	1.6 (0-5)*	0 *	0.7 (0-2)	0	0
Disk Height Reduction ¹	0.8 (0-4)	1.4 (0-5)	0.3 (0-2)	1.2 (0-4)	0.1 (0-1)	0.3 (0-3)
Signal Intensity Reduction ¹	1.6 (0-5)	2.6 (0-6)	0.9 (0-4)	1.8 (0-4)	0.5 (0-2)	1.6 (0-4)

¹ Mean of the sum; ² Data of 5 year follow-on study; * P < 0.05 from EP (O); + P < 0.05 from C (O); ++ P < 0.05 from YP (O).

11.2.3 Statistics

The statistical package used in the statistical analysis was Statview SE + Graphics, Abacus Concepts Inc., USA. Unpaired two-tail Mann-Whitney test was used for comparison of mean Σ grades of disk protrusions, osteophytes, cord compression, signal intensity (SI) in the disks and disk heights in the EP and control groups. A p-value of < 0.05 was considered statistically significant. For the longitudinal comparison within each of the three groups Wilcoxon Signed Rank Test was performed.

11.3 RESULTS

11.3.1 Initial Study

As shown in Table 11-1 for the initial study, the mean sum of osteophyte MRI grades for the EP group was 2.6 (0-13) and was 0.7 (0-3) for the C group resulting in a statistically significant difference. The YP had a mean sum of osteophyte grades of 0.3 (0-2) that was also statistically significantly different from the EP.

The mean sum of disk protrusion/herniation grades for the EP was 3.4 (0-11) and differed significantly from the 1.2 (0-5) score of the control group and 0.4 (0-3) for the YP. There was compression of the spinal cord in 5 EP. This compression was caused by a bulging disk in 3 cases; osteophytes and disk on two disk levels in one case; and, on one level in one case that differed significantly from the C group where no compressions of the spinal cord were found. The YP group also did not have any cord compression.

The mean sum of foraminal stenosis for the EP was 0.6 (0-4) and 0 in the C and YP groups; i.e., this difference was statistically significant.

The mean sum of disk height reduction grades for the EP group was 0.8 (0-4) and 0.3 (0-2) for the C group and was 0.1 (0-1) for the YP group. These differences were not statistically different.

The mean sum of disk SI reduction grades in the EP group was 1.6 (0-5) and 0.9 (0-4) for the C group that was not statistically significant. For the YP the score was 0.5 (0-2).

There was a significant increase in the osteophyte grades at the C₃₋₄ and C₅₋₆ levels, and disc protrusions/herniations at the C₅₋₆ level in the EP compared with the C (Figure 3-1). The disk levels involved in degenerative lesions had a qualitatively similar pattern in both groups with the greatest changes found in disk space C₅₋₆.

11.3.2 Five Year Follow-up Study

During the 5 years that followed the initial study all mean cervical degeneration changes increased for all grading criteria for the three groups, except for cord compression and foraminal stenosis in the YP (Table 11-1). The percentage increase for each criterion was similar within each group but quite different between groups. The mean increase for the 6 grading criteria (range of criteria grading) in the EP group was 87% (50 – 167%); C was 259% (100 – 329%); and YP 124% (0 – 225%). These changes clearly show that the relative increase in the pathologic response of the cervical spine was greatest in the C group and least in the EP.

The sum of the mean cervical grading criteria increased from 9.4 to 17.3 in EP; 3.1 to 11.9 in C; and 1.3 to 3.8 in YP. Therefore the absolute sum of all grading criteria increased approximately the same for both EP and C groups; i.e., EP was still highest by far (Figure 11-1). These data indicate that the G effect is still present but age is becoming an important factor as well, in degeneration of the cervical spine.

11.4 DISCUSSION

Data used in this study is the only G-age control prospective longitudinal research conducted on this topic that has been reported. A similar study is ongoing in Finland (42). Other reported studies are either cross-sectional or retrospective longitudinal, because of time requirements. Prospective longitudinal studies have an advantage over these other types of studies as they are planned before the study begins. Consequently data from them are usually 'cleaner'.

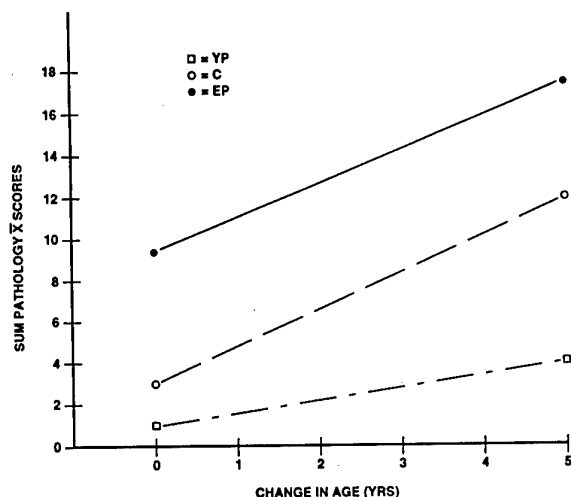


Figure 11-1: Sum of mean scores of grading criteria of cervical degeneration (data from Table 11-1).

The initial study is discussed in some detail in Chapter 3, as it had been published as an abstract and presented at a scientific meeting. The results of that study shown in Figure 3-1 clearly indicate that repeated exposures to a sustained G environment are associated with an increase in the level of cervical spine degeneration. The five year follow-on study is not a continuation of the same trend but finds that the subjects not exposed to increased G are developing cervical spine degeneration at about the same rate as are fighter pilots. Now the importance of age as a significant factor in spinal degeneration has become very clear.

The relationships between exposures to sustained G and aging on cervical spine degeneration are discussed in considerable detail in Chapter 14. These data reported herein (Figure 14-2) and other reports that have considered the aging and G-related processes on this phenomenon have been essential in the development of a model that explains the interactions between G exposures and aging. See Chapter 14.

11.5 SUMMARY

Repeated exposures to increased sustained G accelerates the development of cervical spine degeneration during the third decade of life and is accelerated further during the fourth decade in conjunction with the effect of aging.

* Data used in this report are from a manuscript (to be published) by the same authors of a scientific article on the same topic and from a previous article published also by the same authors (99).

CHAPTER 12

BIOMECHANICAL CONSIDERATIONS IN THE DEVELOPMENT OF CERVICAL SPINE PATHOLOGIES

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12.1 INTRODUCTION

This Technical Report has shown that acute and degenerative types of cervical pathologies occur in pilots of high performance aircraft during exposures to increased sustained G. The evidence regarding this relationship between G and cervical pathologies has come from reports, surveys, and studies of acute injuries involving soft and hard tissues of the neck. Also studies of degenerative changes of the cervical spine have shown increased incidence of cervical pathologies in fighter pilots with histories of repeated exposures to high-sustained G.

However, in order to establish a compelling causal relationship between repeated high-sustained G exposures and certain cervical pathologies, it is important to understand the quantitative and qualitative relationships that exist between applied mechanical forces of various levels of sustained G and the resisting structures of the cervical spine. To accomplish this task, some understanding of the structure/anatomy of the cervical spine and the normal responses of this structure to mechanical forces of repeated sustained G will be presented in this chapter.

There is more interest in and information on spinal injuries caused by impact acceleration forces than by sustained acceleration forces. Also there are numerous impact-injury predictive models. However this information and models are not generally useful for predicting spinal pathologies from repeated exposures to

sustained G. The primary reason that these models are not useful is the involvement of soft tissue structures that support the spine during slower onset of G. Also the intervertebral disk resists applied forces differently depending upon the rate of the application of the force (73). This difference is shown graphically in Figure 12-1.

Preventive strength

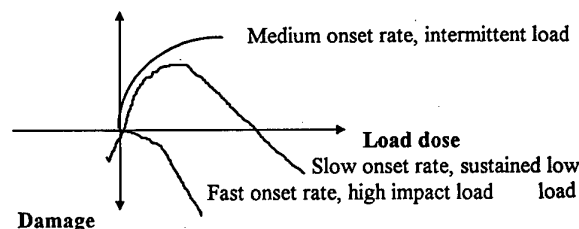


Figure 12-1: Model of different preventive or damaging effects in relation to cervical spine load-dose levels with different G-onset rates or during exercises. Fast onset (during < 1 s), high impact; slow onset (during < 2 s), sustained load; and, moderate onset, intermittent load.

As shown in figure 12-1, at slower onsets of G, the resistance of the soft tissues supporting the cervical spine, principally the muscles and ligaments, play an important role in preventing damage to the cervical spine. Also the mechanical behavior of the disk behaves differently depending upon the rate of application of the force to it. With a rapid application of force (as with impact), the disk behaves like a solid but with slower applications of force (as with sustained G), it behaves like a liquid (73).

12.2 BASIC STRUCTURAL, ANATOMICAL, AND KINEMATICS CONSIDERATIONS

The spine is a mechanical structure made up primarily of vertebrae, intervertebral disks, ligaments, and muscles resulting in a complex system of joints, ligaments, and levers (Figure 12-2). The resilient elastic nature of the vertebral column is provided by the intervertebral disks that make up approximately 30% of the spine (129). The majority of the mechanical stability of the spine is due to its neuromuscular structures and control systems (132). The spine has three functions: (1) transfers weight and bending moments of the head and trunk to the pelvis; (2) allows for motion; and, (3) protects the spinal cord from injury.

The human spine is used to support the body in an upright (bipedal) posture. It was not designed to support such a posture, therefore its design is not optimal for its functional requirements at 1 G. The spine was designed to be a suspension bridge between the front and rear legs of quadrupeds. Consequently the design deficiencies of the spine of humans in support of external loading are amplified and risk of injury are increased as it is exposed to acceleration forces > 1 G.

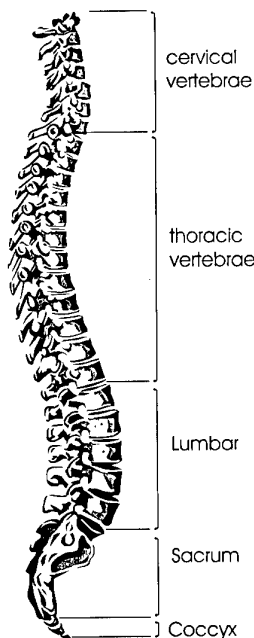


Figure 12-2. Structure of the human spine.

Each vertebra is separated by a flexible intervertebral disk. Six intervertebral ligaments span adjacent vertebrae that articulate with the intervertebral disk and

two synovial joints called "facet joints" providing stability in certain directions. Facet joints are highly innervated thus providing a potential source of neck pain. The highest facet pressures occur with combined torsion, flexion, and compression. Each vertebra is composed of the centrum, neural arch and structures for attaching muscles (i.e., spinous and transverse processes). Each vertebra has two superior and two inferior articulating processes that form half of the facet joint (Figure 12-3). The centrum is supported by superior and inferior margins that are called 'vertebral endplates' (11).

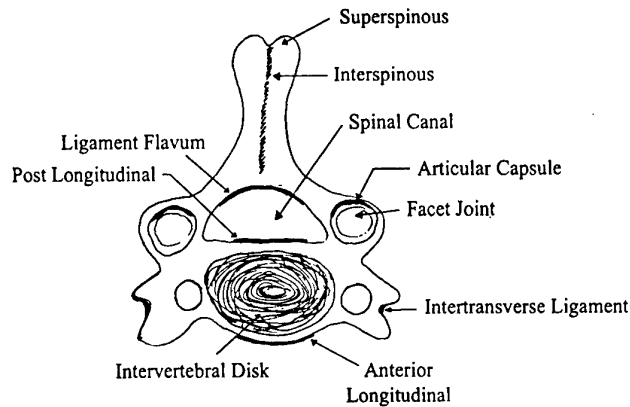


Figure 12-3. Cervical vertebra showing location of ligaments, facet joints, intervertebral disk, and inferior and superior margins (modified from 107).

There are 7 cervical vertebrae with 6 intervertebral disks (C_{2-3} - C_7 - T_1) that provide for articulation of the neck. The curve of the cervical spine allows for shock absorption and is due to wedged shaped intervertebral disks. Along with the facet joints of the vertebrae, the intervertebral disk carries all of the compressive loads of the region of the upper body.

The intervertebral disk is composed of a nucleus pulposus that is a muco-protein gel of fibrous strands surrounded by the annulus fibrosus composed of fibrous tissue in concentric laminated bands (Figure 12-4; 11, 132). The nucleus pulposus behaves with viscoelastic properties. Thus with rapidly applied forces such as with impact, it behaves as a solid. However, with sustained slowly applied forces, it behaves like a liquid (73). Both components of the disks contain collagen and proteoglycans. The former changes little with age but the latter decreases significantly with age. Thus the tensile strength of the disk diminishes with aging. Also the water content of the nucleus pulposus (70-90% by weight) is reduced with age.

Intervertebral disks are attached by connective tissue to the vertebrae while the cartilage endplates separate the disk from the vertebrae. Increasing age destroys the endplates, nucleus pulposus and the annulus becomes fibrocartilage. The intervertebral disk is strongest in its anterior and posterior positions and weakest in the center. Cervical intervertebral disks increase in thickness towards the lower levels of the neck (75).

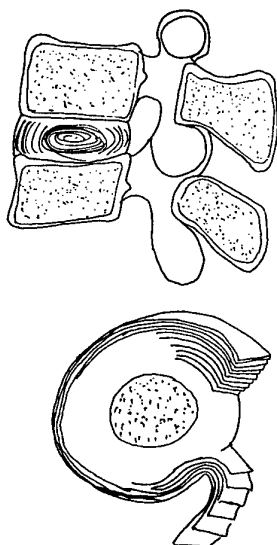


Figure 12-4. Sagittal view of cervical vertebrae with intervertebral disk. Also shown is the annular structure of the intervertebral disk (taken from 11).

Creep and relaxation characteristics of the intervertebral disk are of importance to compression loading of intervertebral disks. The application of a load to a disk causes it to slowly flatten over a period of several minutes. Normal disks flatten less and more slowly with a load than degenerative disks. Recovery to its pre-load height is much slower than the time required for flattening; i.e., repeated loading over relatively short periods of time will cause cumulative increases in creep (132). Intervertebral disk creep has been shown to occur during exposure to sustained G exposures. Hamalainen et al (39) reported that fighter pilots' height was reduced by 4.9 mm following a 40 min exposure to sustained moderate G levels during ACM.

During exposures to sustained-G, the muscles and ligaments of the neck prevent the cervical spine from direct exposure to increased loading (59). Without this protection, the spine is extremely limited with its ability to absorb these energies with only rigid vertebrae and semi-rigid disks. Ligaments of the vertebrae support the

spine in concert with the muscles by providing fixed postural attitudes with a minimum of energy expenditure. Ligaments transfer tensile loads from one vertebra to the other. The main purpose for ligaments is to prevent excessive joint rotation. Failure of the ligament can occur within the ligament or at its attachment to the bone. At relatively high onset rates of loading, failure usually occurs in the ligament.

The maximum voluntary contraction (MVC) of neck muscles and handgrip, respectively, was measured in four male students by Petrosky and Phillips (100) as well as endurance time before fatiguing. While 70% MVC endurance time for the handgrip was 24 s (± 0.07 , SD), it was almost 10 min ($\pm 7:19$, SD) for the dorsal neck extensors, indicating differences in fiber composition. With neck muscle strengthening exercises during 12 weeks, it might be possible to increase neck extensor strength by 33% and the cross sectional area from 19.5 cm² to 22 cm² (21). A maximum voluntary force (MVf) for head extensors is 215 Newtons (N), the resistance applied against the back of the head in young, healthy females and males which translates to a ratio of strength to cross-sectional area of 10.17 N/cm² (82).

The biomechanical properties of the cervical vertebrae and intervertebral disks are unique compared with other regions of the spine (Table 12-1). Vertebrae of the neck have less mass and compression breaking load (CBL) than other vertebrae; CBL of cervical disks are less than 25% that of lumbar disks. The breaking load (BL) of cervical disks are only 27% of those of the lumbar region. However cervical disks have greater ultimate elongation (UE) and ultimate angle of twist (U \angle Tw) properties than lumbar disks (107). The CBL and ultimate compressive strength (UCS) of cervical vertebrae are similar to the cervical disks indicating that either or both will break with external loading. On the other hand, lumbar disks have nearly 3 times the CBL properties of lumbar vertebrae; i.e., lumbar vertebrae will fracture far sooner than the disk will rupture. The majority of the strength of vertebrae comes from the osseous tissue that is greatly reduced with age. A 25% reduction in osseous tissue results in a 50% reduction in bone strength (132). Under compressive loading, the degenerative disk is more greatly stressed. Facet joints may carry up to 33% of compressive loads and share equally with the disks torsional strength.

The cervical spine has the greatest range of motion of any of the other segments of the spine. The ranges of motion (in degrees), as measured from radiographs, of the entire cervical spine for men are: flexion/extension = mean 68 (24-109); lateral bending = 45 (26-81); axial

mean 68 (24-109); lateral bending = 45 (26-81); axial rotation = 145 (90-200); rotation from flexion = 71; and, rotation from extension 162 (Figure 12-5) (76, 25, 137). The combined limits of ranges of motion of individual interspaces of the lower cervical spine are: flexion/extension has a range of 2 - 36 degrees; lateral bending 0 - 20 degrees; and axial rotation 5 - 28 degrees. Most of the motion of the lower cervical spine is in the extension/flexion directions with the C₃₋₄, C₄₋₅, and C₅₋₆ intervertebral spaces having the largest mean ranges at 14-16 degrees with C₆₋₇ next with 11 degrees (76).

Table 12-1. Biomechanical properties of the wet human cervical spine are compared with the lumbar spine (taken from 107).

Average Adult Values for Vertebrae ¹			
Region	U. C. S. (kg/mm ²) ¹	C. B. L. (N) ¹	U. Ct. (%) ¹
Cervical	1.03	3089.2	6.6
Lumbar	0.54	4952.5	4.5
For Intervertebral Disks (40-59 yrs age)			
Cervical	1.08	3138.2	35.2
Lumbar	1.12	14710.0	35.5
Average Tensile Values for Intervertebral Disks			
Region	U. S. (kg/mm ²) ¹	B. L. (N)	U. E. (%) ¹
Cervical	0.30	863	77
Lumbar	0.26	3187.3	59
Average Torsional Values for Intervertebral Disks			
Region	U.T.S. (kg/mm ²) ¹	B.M. ¹ (N•M)	U. ∠ Tw. ¹
Cervical	0.48	5.0	34°
Lumbar	0.45	26.0	17°

¹ U = Ultimate; C = Compressive; S = Strength; B = Breaking; L = Load; Ct = Contraction; E = Elongation; T = Torsional; M = Moment; Tw = Twist.

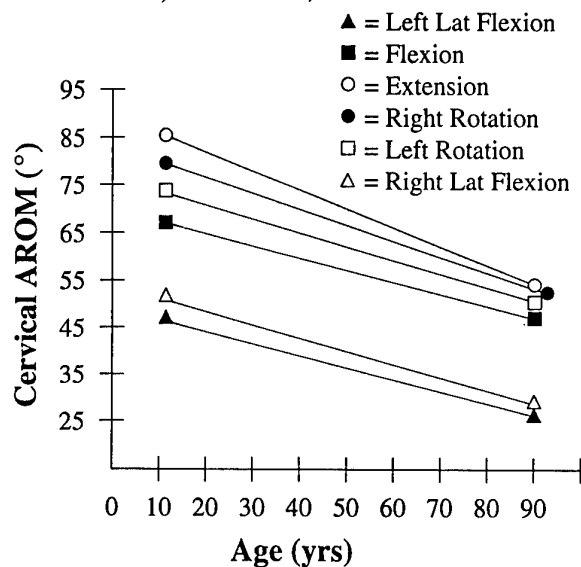


Figure 12-5: Relationships between active range of motion (AROM) and age in males (taken from 137).

However all of these cervical joints have similar ranges of articulation in the sagittal plane and are the most flexible. A causal relationship at these interspaces with an increased incidence of cervical degeneration may exist since similar joints are involved (Chapter 3). Disk degeneration reduces these ranges of motion (12). The pattern of motion of the C₆ had the steepest arch with C₂ having the flattest. The acuity of this arch motion is decreased with disk degeneration (132).

Age reduces ranges of all active range of motion (AROM) and this relationship with age appears to be rectilinear (Figure 12-5). From 20 to 59 years of age loss of ranges of all other motions each is approximately 9% (25).

12.3 BIOMECHANICS OF CERVICAL SPINE LOADING IN PILOTS

The numerous muscles and ligaments that support the cervical vertebrae provide for head extension, flexion, rotation and combinations of extension: flexion with rotations. Head motion for the general populous is usually rotations, extensions and flexions of 45° or less. Pilots of high performance aircraft, however, significantly expand that envelope especially regarding head rotation in flexion: extension combinations; e.g. checking "six" as they attempt to look aft of the aircraft. These unusual head positions occur frequently with exposures to sustained G during aerial combat maneuvers (ACM). The ACM is an air to air maneuver that is particularly common during combat and training as fighter pilots continuously examine the air space behind them for the enemy. It is a reality, therefore, that a substantial portion of a pilot's time during ACM is checking their six positions to the right and left that involves extension: flexion motions of the head in various combinations in rapid order. In addition, the head is contained within a helmet with attached equipment including an oxygen mask and perhaps night vision goggles that add significant mass (1.2-3 kg) above the neck.

The ACM is a maneuver that is usually a continuous event that can last a few seconds to several minutes per sortie and there can be several sorties per day. Pilots usually fly many days per month. It has been calculated that pilots over their lifetime can be exposed to a total of 720 hours of increased-sustained G representing 90 working days, of which much of it is at 6 G and above (3). Therefore, sustained G exposures over the lifetime of a fighter pilot provide an environment with a sufficient time period to allow degenerative changes of the spine. Of course, to get degenerative changes more

severe than non-exposed individuals, G loads acting on the spine must be sufficiently high and frequent in occurrence to manifest these types of pathologies.

Biomechanics of the cervical spine as it relates to spinal pathologies of pilots from repeated exposures to increased sustained G loads, involve many factors that are specific to the environment of the fighter pilot. These many factors are listed below:

- mass of the head-worn equipment, e.g., helmet, oxygen mask, night vision goggles;
- mass of the body segments head and neck;
- location of the center of gravity (c.g.) in relation to the motion axis of the cervical spine;
- head-and-neck position, i.e. the neck flexion angle and the direction of flexion;
- aircraft angle of attack, i.e. the alpha angle;
- G-load, which multiplies the weight of the mass by the level of G;
- movement speed, causing acceleration and deceleration forces;
- muscle activity due to exerted hand and arm forces, trunk inclination (backwards inclined more favorable than upright or flexed), cervical breathing muscle exertion as it relates to the AGSM that adds to the load in all neck positions;
- specific task requirements with high precision work for vision, head movements and arm-hand forces sitting in a restricted position for a long time entail levels of muscle activity that adds to the related load;
- muscle and ligament condition, strength, and fatigue; and,
- psychological stress, which causes an increase in physiologic (e.g., muscle) activity that increases the rate of the development of fatigue.

It is clear therefore that many of these factors are unique to the high-G environment, several of which increase significantly the risk of cervical injury from external loading. In addition, it is also important to realize that biomechanical data are not available for several of these variables. Therefore models must be used to estimate biomechanical force/structure interactions as they relate to aircrew in the high-G environment.

These interactions between the external load and the cervical spine have a basic structure that is described in figure 12-6.

12.3.1 Considerations in Assessing the Effects of External Load on the Cervical Spine and Related Structures

External loads are resisted by the cervical spine using a combination of structures that function as a single-integrated unit. Failure of one structure places additional mechanical stress on the remaining structures thus reducing the capability of the total resistive structure. Major structures in support of the spine are muscles that play an important role in the normal functioning of the spine. The roles of the muscle components on lumbar spine mechanics have been modeled in a finite element study based on two motion segments (71). By decreasing muscle effectiveness, the model found that during lifting, muscle dysfunction destabilized the spine, reduced the important role of the facet joints in transmitting loads, and shifted loads to the intervertebral disks and ligaments. It is anticipated that the cervical spine behaves in a similar manner with neck muscle dysfunction.

The ability of the cervical spine to counteract compressive loads is optimal while the head is in a neutral position, i.e., with a slight cervical lordosis (Figure 12-7A). Facet joints normally guide the direction of movement of the neck. Shear forces in the spinal-flexed positions expose these facet joints, which are then more vulnerable to increased G. The effects of increased G do not only depend upon the level of the G but also the G duration, number of repeated exposures and the duration of rest periods between exposures.

Forward flexion of the cervical spine widens the nerve root channels. However, excessive loads in this flexed position increase the risk for ligament injuries and/or vertebral compression fractures (Figure 12-7D). Also there is an increased risk for disk protrusion when the neck is in the flexed position. Neck extension (Figure 12-7C) or extension in combination with lateral head flexion and rotation decreases the width of the nerve root channel, increasing the risk for nerve root injuries. During these combined movements, the facet joints are compressed and brought to their maximum closed position. Therefore, increased combination movements will also greatly increase the risk for hard tissue and soft tissues (capsule and cartilage) injuries.

In the middle of the joint surface, the cartilage is thicker, whereas in the peripheral areas the cartilage, it is thinner. This means that the load absorbing capacity of the joints is greatest when the head is in a neutral position (Figure 12-7A). Forces that are tolerated when the head is in the neutral position can exceed the

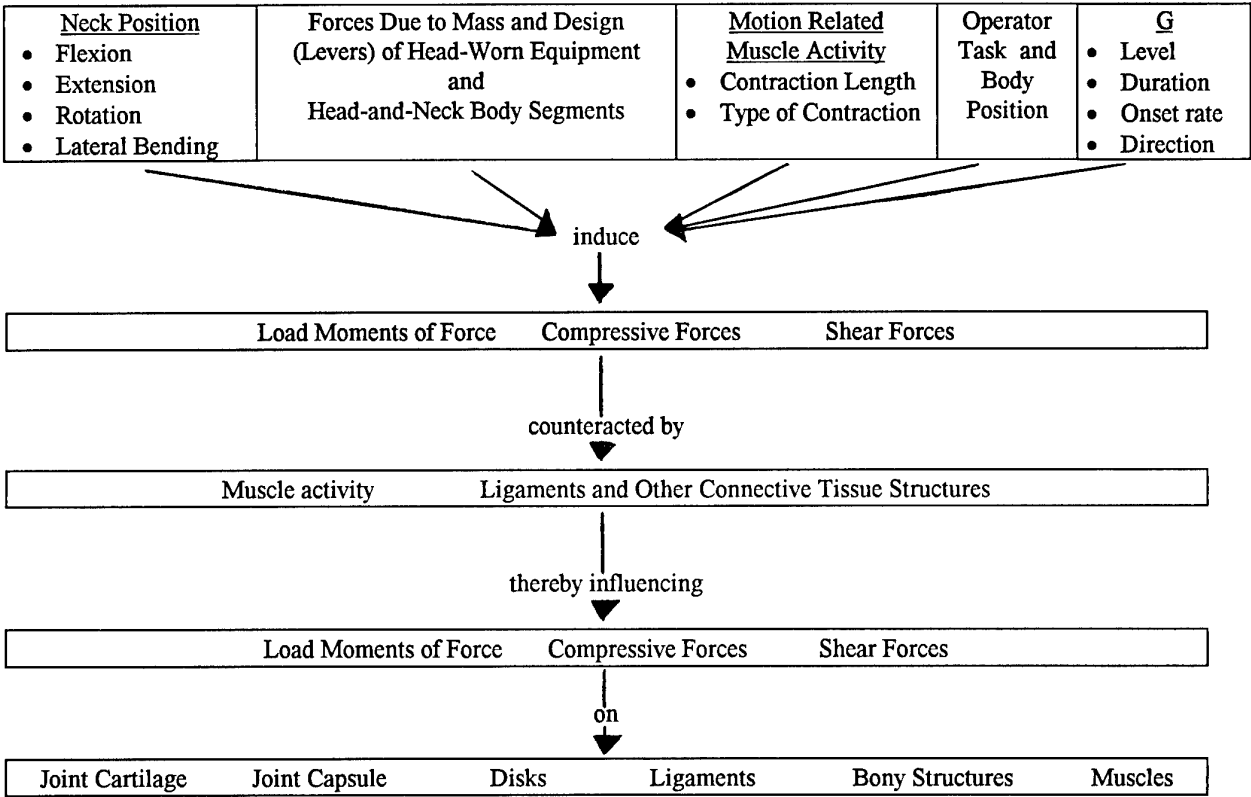


Figure 12-6: Factors of importance and how they interact in understanding the external cervical load on cervical spine structures of fighter pilots.

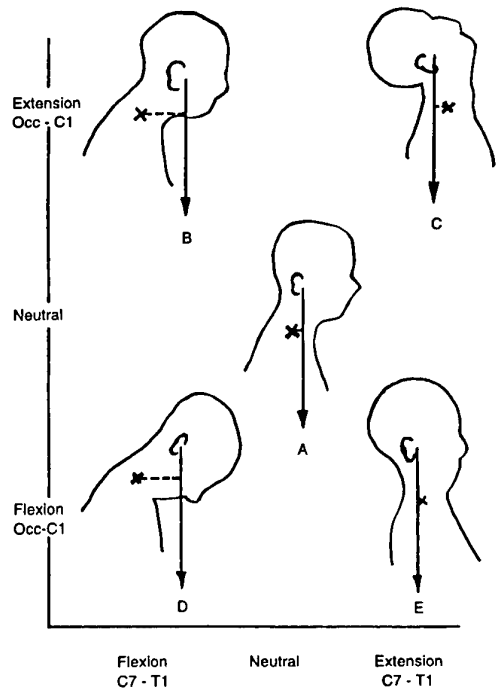


Figure 12-7: Head and neck neutral and extreme positions in the upper (Occ-C₁) and lower (C₇-T₁) cervical spine, and entailed changes in lever (moment) arms inducing changes in load moment of force around the bilateral motions axis of C₇-T₁ (Nm at 1 G). A: Neutral (1.2 Nm); B: Flexed lower – extended upper (3.7 Nm); C: Extended upper and lower (-1.7 Nm); D: Flexed lower and upper (4.3); E: Extended lower-flexed upper cervical spine (-0.4 Nm). (Modified from 49).

strength limit of the cartilage when the head is flexed, extended and/or rotated (Figure 12-7).

In a neutral spine position, the ligaments tend to be relaxed and provide less support to the neck (97) increasing the demands on muscle activity to stabilize the system (18). However, as the range of motion of the head increases, the ligaments and connective tissues from the surrounding muscles begin to provide a counteracting force (Figures 12-7 and 8). During extreme ranges of motion, muscles can become inactive even with a large induced-load moment (49).

Interestingly therefore positioning the head-and-neck in such an extreme position, that does not require muscular activities may be used by pilots with less muscle strength while pulling G during an ACM; despite shortening in levers of counteracting structures entailing higher loads.

Ligaments have a structural design that will withstand large forces. However, with their short moment arms, the ligamentous counteracting forces will add more to the compressive forces than would muscles that counteract the load moment with their longer moment arms. Thus pilots with strong neck muscles will be able to choose head-and neck positions; selecting those with less load on the cervical spine joint structures.

During neck rotation, there is not an increase in load moment so long as the movement is performed around the longitudinal axis in the neutral position (Figures 12-7 and 8). However, the connective tissue structure of the ligaments will resist this movement and increase muscle activity (78). In a rotated position, this increased muscle activity adds to the compressive forces on the spine because of the stretched muscles and ligaments. This increased compressive force of the spinal tissues is added to G-induced force due to weight on the head-and-neck from the head-worn equipment. This type of head-and-neck rotation movement, rapidly changing in different directions, is commonly performed during the ACM.

The maximum voluntary strength requirements are highest for eccentric muscle contractions (muscle lengthening), slightly less for isometric, and lowest for concentric contractions (muscle shortening). Muscle activity that moves the head-and-neck during increased G will, because of the acceleration/deceleration of the muscle movement, add to the external induced load moment. It is well known that moving the head-and-neck while pulling G, as experienced by pilots, sometimes induces acute cervical muscle injuries. However it is not known how much the force, due to this movement acceleration/deceleration, adds to and interacts with the G-load. Generally biomechanical models consider only static situations. Pilots should be made aware of this increased risk for neck injury and avoid head-and-neck movements while pulling G. Ironically, this awareness is particularly important for pilots with strong necks since pilots with weaker necks will not be able to move their heads during high levels of increased G exposures.

The duration of isometric muscle contractions is limited because of the onset of muscle fatigue. Muscle fatigue reduces the force (e.g., load moment of force, Nm) that can be exerted, while muscle endurance is the time duration (s) that the muscle can provide a specific force. An important factor that influences the time course for fatigue and endurance is the percentage of the muscular strength utilized during the contraction, the duration of the contraction and the rest periods between

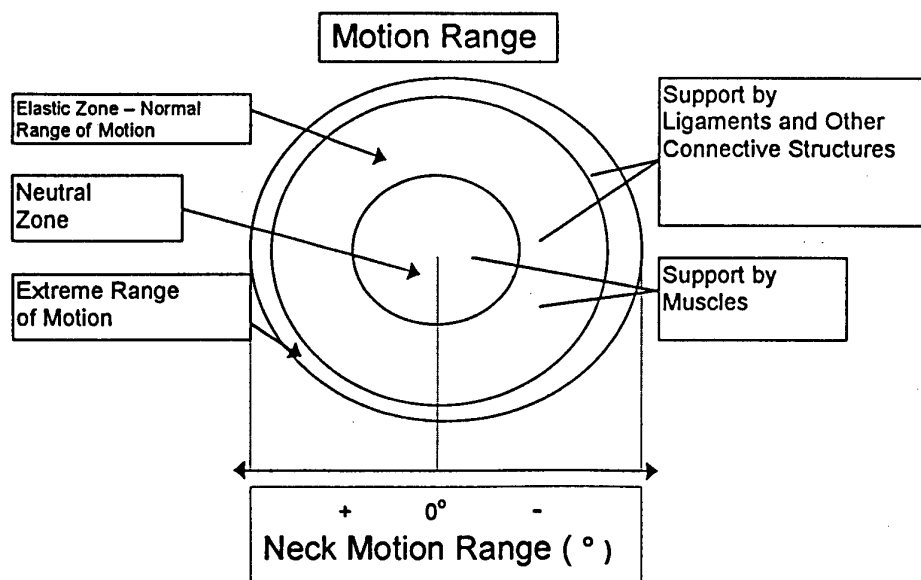


Figure 12-8. A schematic model of load-counteracting structures in different parts of the motion range (looking down on the top of the head).

contractions. Pilots hold their head for extended periods of time in a position that is best described as an extension of the upper neck and flexion of the lower neck (Figure 12-7B). This position that can be maintained for several hours requires continuous muscle activity in the upper cervical spine and entails increased load moments of force that can be quite fatiguing to neck muscles. Muscles that are fatigued before exposure to sustained G are less capable of supporting the cervical spine and at risk for acute injury. Pilots who regularly experienced neck pain had shorter endurance times in the neck flexor muscles compared to those who rarely experienced neck pain (54).

The accumulation of lactic acid is painful and occurs as an immediate response during fatiguing contractions, whereas muscle soreness that occurs the next day is a response to over exertion and not fatigue. Incidentally, the muscle is more vulnerable with eccentric movements (lengthening) than concentric actions.

The maximum muscle strength capacity remains relatively constant over the forward-flexion motion range (52). Therefore a continuous increase in load moment due to increased moment-arm (lever arms) lengths with increased cervical spine flexion requires proportionally more muscular utilization for counteraction (Figure 12-7). Compared to a neutral upright cervical spine position (49), the load moment required for the extensors of C₇-T₁ vertebrae to counteract the forces with the head in a maximum flexed neck position is increased 3.6 times. Surprisingly it is increased a large 3.1 times with the head in a simple position with the lower neck flexed and the upper cervical spine extended; i.e., a common neck position used by pilots during long duration missions as they check the Head Up Display (HUD; Figure 12-7B).

In the "check-six" position, the neck extensor muscles only act in a co-contracting activity (opposing extensors contracting at the same time) to stabilize the neck. Whereas the forward flexors/rotators and lateral flexors provide the strength required to counteract the load moment. In a neck position with backwards extension (similar to check six) of the head, the load moment of the lower and upper cervical spine used by the flexors is 1.4 times that of the extensors in a neutral position. In addition, the flexors are generally weaker and their moment arms are significantly shorter than the extensors (79). Consequently a relatively low-load moment being counteracted by the flexors may exceed their maximum strength capacity and induce a high neck compressive force. On the other hand, the extensors will be able to counteract the same external

load level with less muscular compressive force. In the check-six position, the stabilizing co-contractions required of the extensors will add to the mechanical load on the cervical spine (18, 49).

A schematic of a model of load-counteracting structures in different parts of the motion range is shown in Figure 12-8. In the Neutral Zone the ligaments are relaxed thereby requiring muscular activity to stabilize the head. With head movement into the Elastic Zone the ligament begins to tighten (18, 97) and acts with muscle contractions counteracting the induced load. With the head in the extreme end of the range of motion (i.e., extreme position) only the cervical ligaments and connective tissue surrounding the muscles, counteract the G (50) and they are maximally stretched. Continued overexertion will cause soft tissue injuries to the cervical spine.

While fatiguing muscle work rapidly causes lactic acid induced pain, overexertion of ligaments and other connective tissue structures provokes delayed pain, the intensity of which is dependent upon the G magnitude and flexion direction. Experimental studies of young females who never experienced neck pain (50), showed that a moderate load (the weight of the head-and-neck) held in an extreme forward flexed neck position caused pain when maintained several minutes. They continued this position for several more minutes that in the beginning was slightly painful, until they voluntarily stopped because of the severity of the pain.

Although the pain disappeared after moving the head from the painful position, it sometimes reoccurred within the next 24 hours and lasted a couple of days. This reoccurring pain suggested the possibility of overexertion of the ligaments, connective tissues and muscle insertions in the neck region. Overexertion that leads to failure and ruptures of these structures will cause reoccurring pain over a considerably long period of time (Figure 12-1).

When high, fatiguing and thus painful muscle contractions are required, and/or with a minor, painful muscle insertion injury causing pain at high loads, the pilot might be more prone to keep the head in positions supported by ligaments and capsules rather than putting strain on the painful muscles. The relative shorter lever arms of connective tissues, compared to muscles, induce higher forces with possible failure of these structures and higher loads to be borne by the bony structures of the spine. This additional load on the spine can cause acute spinal injuries (e.g., vertebral disk herniation) or

with subacute injuries to the spine repeated over a sustained period could lead to spinal degeneration.

It is clear therefore that it is extremely important to develop strong neck muscles that are critical in supporting/protecting the cervical spine; particularly in an environment with high load demands on the neck.

12.3.2 Prevention and Treatment of Acute Cervical Injuries

12.3.2.1 Prevention of Cervical Injury from Overload

Acute cervical injuries sustained during high-sustained-G exposures are caused by the rapid application of increased external load to the neck. Sufficient information about muscle and ligament overload specifically of the cervical region is not readily available. Therefore much of it must be obtained from studies involving other regions of the body that are prone to injury in common athletic sports. In sports medicine, muscle injuries such as sustained by pilots exposed to high-sustained G that involve their necks are commonly referred to as overload injury from overtraining. Muscle overload injury is the most common type of athletic injury comprising about two thirds of all sports injuries (66).

Overload injuries occur because of the amount of the force and/or frequency of application of the increased force. The latter is a particularly common cause of injury as the body has not had sufficient time to recover from the exercise regimen. The former, however, is probably the most common model for neck injury in fighter pilots although muscle fatigue may be a factor. There are two types of musculotendinous overloads:

- (1) absolute tensile overload where the applied force is too great at the outset for the musculotendinous unit; and,
- (2) relative tensile overload where the application of the force is repeated too frequently or for too long decreasing the ability of the musculotendinous unit to tolerate the applied force.

Prevention of overload injuries with resistive training of muscles and joints is based on several facts: (1) stronger muscles absorb more energy; (2) increases structural strength at the joint including ligament-bone junction strength; and (3) increases the Muscular Utilization Ratio (see below). Mechanisms have been identified that suggest muscular strength is a factor in injury prevention. A decrease in the rate of a sport injury caused by a specific resistance training regimen has not

been demonstrated (66). This finding is similar to our experience regarding neck muscle training in preventing cervical injury with increased G; i.e., there are numerous reasons why it should work but we haven't been able to prove it.

On the other hand, Fleck and Falkel (27) report that there is evidence that resistance training can aid in injury prevention. They note that research indicates that resistance training promotes increases in the strength of ligaments, tendons, their attachments to bone, joint cartilage, muscle connective tissue, and bone mineral content. The increase in mineral content of bone may aid in prevention of injuries to the bone. But in order to accomplish these benefits, muscle strength must be balanced between agonist and antagonist muscles that are used in a particular sport. This training supports the first type of musculotendinous overload.

Ringdahl et al (54) reported that fighter pilots with neck pain had shorter endurance times for neck muscles than pilots resistant to neck pain. This finding supports the second type of musculotendinous overload.

Overload injuries can be reduced with proper musculotendinous warmups before applying the load and resistive training for muscle strength that replicates the same sport activity. The former has been identified in reducing neck soft-tissue injuries from sustained-high-G exposures (127). Dynamic neck exercises that replicated neck movement during the ACM appeared to be effective in reducing acute neck injury (40).

Cervical muscles are the primary support system of the neck and probably key in protecting against spinal degeneration. When muscle strength increases, the relative load on the muscles for a fixed workload as a % of Muscular Utilization Ratio (Muscle Moment of Force Required/ Maximum Muscle Strength) decreases, that will decrease the risk for overexertion injuries (52, 55). Resistive exercises also increase the joint structural strength. Therefore, theoretically it is important for pilots to develop strong muscles that will be useful during their flying missions.

Unfortunately no controlled studies have been conducted on fighter pilots to determine the benefits of increasing cervical muscle strength. Recently Hamalainen et al (44) conducted a longitudinal study with fighter pilots comparing increases in neck muscle strength with the incidence of acute neck injury during ACM flying. Mean muscle strength increased 4 to 19% using either weighted helmets or dynamic neck exercises 3 times each week for one year. Dynamic neck exercises were

most beneficial even though muscle strength increased similarly in both groups. Pilots not flying due to neck injury were reduced from 9 of 10 during the year preceding the study to 4 of 10 during the training year.

It is well known from physiological studies, that to be effective, a particular type of muscle training exercise must replicate its intended application; i.e., using the same types of contraction and joint angles (67). Also it is agreed that exercises 3 times a week are needed for optimal strength improvements, whereas exercises once a week are required to maintain muscle strength. Muscle exercises first cause an increase in muscle coordination (during first three weeks), thereafter structural changes in the muscle occur (during the next two to three months) and finally the ligaments and connective tissue are strengthened (during the following six months to one year).

Conley et al (21) found that those who exercised with 3 x 10 repetitions of neck muscle resistive exercises in addition to more conventional resistance exercises during 12 weeks, improved their neck muscle strength. The other group without neck exercises only increased general body muscle strength. Thus pilots should perform neck muscle training exercises to increase strength and muscle endurance that support head and neck movements (concentric, eccentric and isometric) similar to those that will be required to accomplish their mission.

12.3.2.2 Treatment/Rehabilitation of Cervical Injuries from Overload

Acute neck injuries from exposure to high-sustained G, regardless how minor, demand the use of a rehabilitation program. Subclinical soft tissue injuries if not treated properly can lead to overt injuries with greater delays in returning to pre-injury form. The key in the treatment of any overload injury from overtraining is to allow sufficient time for healing. However, the rehabilitation program should be one that returns the pilot to flying status as soon as possible without minimizing the importance of the injury and taking steps to prevent further injury or its reoccurrence.

Traditional goals of a sound rehabilitation regimen are: (a) accurate diagnosis; (b) proper treatment; (c) allow time to heal; (d) maintain other aspects of physical fitness; and, (e) regain complete function. Methods used in accomplishing these goals are: (a) protect the injured tissues; (b) proper application of therapeutic techniques; (c) rehabilitation of muscle flexibility, strength, and balance; and, (d) proper assessment of the progress of

the rehabilitation. The process is divided into three phases: (1) acute phase that protects the injury; (2) recovery phase that returns the pilot to pre-injury form; and (3) maintenance phase that increases muscle strength, flexibility, and balance above pre-injury levels (66). More detailed information on this topic can be obtained from an excellent review by Kibler et al (66).

12.4 MECHANISMS INVOLVED IN THE DEVELOPMENT OF CERVICAL SPINAL DEGENERATION

12.4.1 Process of Degeneration

This section is not a comprehensive review of degeneration of the cervical spine, but it is necessary to develop some understanding of the processes involved with spinal degeneration that naturally occurs with aging. This information will be used to explain degenerative changes associated with external loading situations on the spine with increased sustained G. Spinal degeneration of vertebrae is frequently preceded by acute injuries of the neck and degeneration (deterioration) of vertebral disks.

Spinal degeneration is a term that denotes several changes in the structure of the spine that usually suggests the occurrence of some forms of deterioration. There is not a specific criterion that denotes spinal degeneration. Indeed several criteria are used to define its existence. These criteria are usually graded (scored) as to their level of change from normal with subjective scoring. The degree of degeneration is determined by the number of criteria involved and their level (score) of change. The most commonly used criteria to define and measure degeneration of the spine using MRI or radiographs are: (1) decrease in disk height (disk space narrowing $\geq 50\%$); (2) disk protrusion (bulging); (3) osteophytes or vertebral spurring (spondylosis); and, (4) increase in disk density (MRI signal intensity). Also used but with less frequency are: (1) irregularity of endplates and (2) vertebral cartilage loss (14, 109, 121). Scores for degree of change for each criterion are arbitrary commonly 1-4 with 4 representing the greatest degree of degeneration. Frequently scores for all of the criteria are summed to provide a single score of level of degeneration.

Disk degeneration is a common aging process that begins at the end of the second decade of life. By 40 yrs of age, all disks have some form of degeneration. Approximately 40% have moderate to severe degenerative changes. Disk protrusion is believed to be

a combination of disk degeneration, excessive loading, and perhaps disk fatigue. Endplate failure from excessive loading may contribute to disk degeneration (11).

The most frequently affected cervical disk areas with aging are C₄₋₅; C₅₋₆; and, C₆₋₇ (84). The relationship between types of disk degeneration and mobility of specific cervical vertebrae is obscure. It is assumed that acute disk damage can lead to disk degeneration yet disk degeneration may be necessary for certain types of acute disk damage (41). Aging also decreases trabecular bone mass of spinal vertebrae although less in the cervical spine. Interestingly no bone loss was found in C₃ and C₄ vertebrae (32).

The exact mechanisms that lead to premature spinal degeneration especially with external loading, are not known. Our hypothesis assumes that with repeated loading on the spine from increased G, degenerative changes will occur more rapidly than with normal aging. The exact process by which this occurs remains a mystery, but there is evidence that mechanical stress will accelerate the process usually because of subacute disk injury. In the normal aging process, the number of living cells in the intervertebral disks is decreased that reduces its ability to absorb loads. Thus "usual loads" cause disk damage with the beginning of degenerative changes. Theoretically this process can be accelerated with compression stress that has been shown to acutely damage endplates and the disks. Disk fatigue from overloading involving flexion, either continuously or cyclic, results in annulus distortion with radial fissures (1). Disk damage is exacerbated with torsion stress and combinations of neck flexions (41).

An interesting aspect of spinal degeneration is the development of osteophytes. Nathan (89) reported on an extensive study of osteophyte formation of 400 vertebral columns of cadavers. The development of osteophytes begins in the twenties and by the forties all spinal columns had osteophytes. Osteophytes are developed in many different ways but usually involve vertebral ligaments and/or disk pathologies. The vertebrae C₅ and C₆ were the most common cervical locations. This site is the location of the peak of the cervical curve where loading pressure is the greatest. The C₄ and C₅ are at the apex of the angle during hyperextension and C₅ and C₆ are at the apex of the angle formed by hyperflexion. He considered the formation of osteophytes as a defense mechanism (i.e., increase structural support of the spine) against that pressure. This pressure is a function of gravity and increased external loading. Nathan (89) theorized that

osteophytes begin to form when compression forces on the vertebral endplates exceed the resistance capacity of normal vertebrae. He noted that even young people develop osteophytes with heavy labor and strenuous sports. Degeneration of intervertebral disks with physiologic loading (compression forces) leads to the formation of osteophytes with the loss of their shock-absorbing capacity. Degenerative changes of C₅₋₆ disk are most common of the cervical spine (115).

Recent animal research using finite element analysis gives a theoretical model of how spinal disk degeneration with external loading develops (80). Lotz et al (80) reported on a mouse model that sustained spinal compression on the intervertebral disk of the tail for only one week. Results of their studies and their finite element analysis have demonstrated how external (physiologic level) loading of the spine can result in subacute injury eventually resulting in disk degeneration.

After one week of spinal compression, they (80) observed several pathologic consequences that suggested the beginning of the development of spinal disk degeneration with many similarities to the human spine. Specifically these changes included disorganization of annular architecture, increased biomechanical instability, altered collagen type-II and aggrecan mRNA expression and reduced cellularity. Several of these changes are similar to those observed in human disks at the beginning of the degenerative process. Annular morphologic changes including the development of degradation of the collagen lamella of the inner annulus and fibrocartilage within the middle annulus were reported.

They concluded that static compression of the disks causes cell death in the nucleus and inner annulus due to a change in cell shape with a change in the mechanical strain or an unfavorable biochemical environment produced by water loss. They postulate that this loss of nuclear volume leads to disorganization of the lamellar structure of the inner and middle annulus by unloading of the collagen fibers. Sufficient cell death will prevent the disk from recovering after the load has been removed. The result is a chronic state of compression of the annulus that changes fibroblasts to chondrocytes with the production of fibrocartilage in the annulus; i.e., the development of annular degeneration.

Another animal model using sheep examined the relationship of acute injury of the annular region of the disk in the disk degeneration process. Osti et al (95) injured the disk annulus with 4.5mm stab wounds and

found that as it healed, it appeared to accelerate the biochemical degeneration of the nucleus pulposus. Similar damage to the lumbar annular disk has been accomplished with fatigue loading in compression and bending using human cadavers (1).

Extrapolation of the results of these animal studies to the neck of a pilot is not difficult. Even though the external load on the neck of the pilot is not continuous for a week, the results of disk shape changes and the effects of external loads are not immediately relieved at the end of the increased G exposure. Disk creep response sustains the disk shape changes and therefore the forces on the structures within the disk after the load is removed. Conceivably with some deformation of the disk remaining, the pilot enters into another ACM thus returning the load to an already deformed disk, thus exacerbating the condition. Thus some level of spinal disk deformation in the cervical spine will remain for several minutes. Enhancing this situation is the unstable load moment placed on cervical vertebrae during head movement of the pilot during the ACM. Additionally unstable head positions and movements under increased G may produce minute injuries to the disk annulus that could exacerbate the onset of cervical degeneration. The specifics of head movements of pilots flying air combat aircraft follow.

12.4.2 Occupational Relationships

Premature onset of degeneration of the cervical spine has been reported in rugby players with increasing age (109). The disk spaces most frequently involved were the C₄₋₅; C₅₋₆; and, C₆₋₇. Although the head loading in this situation is probably more abrupt than for fighter pilots, it must be remembered that fighter aircraft can have G onset rates of 10 G/s.

Scher (110) also studied women carrying loads > 90 kg on their heads for many years. He found no cases of premature cervical degeneration, but they maintained a neutral head position which provides maximum support of the head with the best balance of load moments of force; i.e., the cervical disks are probably best protected in this head position. These findings are similar to those reported by Levy (75) concerning cervical injuries to porters who also carried heavy objects on their heads. If the load moves from the neutral position on the head, severe injuries can result (Figure 12-7A; compare compressive forces at 9 G, Figure 12-13).

12.5 EFFECTS OF THE FLYING ENVIRONMENT ON THE CERVICAL SPINE

12.5.1 Exposures to High Sustained G

Hamalainen et al (39) measured a reduction of 4.9 mm of spinal height of pilots following 40 min of exposures to ACM. This amount of spinal shrinkage is equivalent to bearing a 10kg barbell while standing for 20 min. Clearly the ACM environment has a direct effect on the spine with external loading.

12.5.2 Seat-Back Angles

The seat-back recline angle will probably influence the level of neck muscle activity during a flying mission; i.e., greater seat back angles will reduce neck muscle activity and lessen muscle fatigue. It has been shown (111, 112) that while seated in an upright seat, arm work in a flexed trunk posture (slouched), causes higher neck muscle activity than in an erect trunk posture (Figure 12-7). The same head position in a backwards reclined trunk posture will require even less neck muscle activity. Thus it is likely that increasing the seat back angle will reduce not only lower back pain (7, 8) but also neck pain.

12.5.3 Head-Neck-Body Positions in the Aircraft

Rudder-pedal work decreases the ability to change the seated position during missions. Therefore, because of muscle forces in the hamstrings in this position, the pelvis is rotated backwards causing a lumbar kyphosis that increases thoracic flexion. A flexed trunk posture will increase neck flexion that will add external load to the neck extensors (112).

The fixed seated position with forceful arm movements in controlling the aircraft stick while performing head-and-neck movements will, with neck muscle activity, increase the cervical spine load (51). Also, with arm movements the upper *trapezius* and the *levator scapulae* become involved and resist neck movement, thus directly and indirectly adding to the compressive force of the cervical spine (113).

As discussed earlier in this Chapter, a typical head position for a pilot using the HUD is a lower neck flexion with an upper neck extension. This posture will increase the load on the lower neck extensors 3.1 times over the head being in a neutral position (Figure 12-7B). These increased loads accelerate the development of neck muscle fatigue perhaps with reduced blood

circulation and may reduce disk nutrition. These physiologic consequences are discussed below.

During ACM, with the head in a rotated "check six" position, increased cervical muscle activity adds to the compressive forces on the spine because of the stretched muscles and ligaments. Besides frequently performed head-and-neck movements, the flying mission also entails high demands on precision work that is known to add continuous activity to the neck-and-shoulder muscles. The demands on vision, where instruments need to be checked, are competing with other senses for postural alignment. Stabilizing the head, while performing precision hand-arm work during high G, may result in long periods with static continuous neck-muscle activity. For proper muscle blood circulation with static muscle activity for longer than one hour, levels of contraction should not be greater than 5 % MVC (63). In addition, the mechanical load on the cervical spine increases with increased muscle activity, due to the directions of the muscle fibers. Also since the disks receive their nutrition by changes in load (64), periods with high continuous loads might result in reduced disk nutrition with an increase in the rate of disk degeneration.

12.5.4 Aircraft Angle of Attack

The aircraft angle of attack (i.e., the alpha angle) is high only during low G. Therefore its role in neck muscle activity as it relates to high-sustained G is not a major one. However the aircraft angle of attack is additive to the seatback angle discussed above in 12.5.3. Thus those effects are amplified with any angle of attack that is present in an ACM. Of course the head position of the pilot will define the final neck muscle activities. Due to the magnitude of the angle, depending on the head-and-neck positions, pulling G either reduces the flexing cervical spine moment in the lower cervical spine, or it may lead to an extending load moment that the flexors will have to counteract (54, 55).

12.5.5 Personal Equipment

The design of the life preserver can restrict the mobility of the cervico-thoracic vertebrae C₇, T₁₋₃, that causes an increase in the mobility required of the other cervical motion segments for the check-six position. Also being strapped firmly to the seat and the parachute harness restricts the ability to perform some of the required neck rotation movement in the upper thoracic spine (53, 77).

Wearing glasses or other vision-restricting devices is another problem that increases the demand for neck rotation since peripheral vision may be restricted.

12.5.6 Performing the AGSM

The cervico-costal muscles (muscles that attach to the cervical spine and the first two ribs) are used in performing the AGSM. Because of the direction of their contraction during the AGSM, an additional compressive force is applied to the cervical spine as well as restricting its movement. Of course increased G during the ACM directly adds compressive forces to the cervical spine. Additional compressive forces from the weight of the stomach and the lungs with an increase in G, pulling on neck muscles, could also be a factor if the subject is not wearing the anti-G suit. However with the inflation of the abdominal bladder of the anti-G suit, the diaphragm is raised during increased G thereby eliminating this additional compressive force on the cervical spine (17).

12.6 BIOMECHANICAL MODELS OF HEAD-AND-NECK LOADS OF PILOTS DURING INCREASED G

12.6.1 Models Applications

In Chapter 2, it was shown that a principal extensor muscle of the neck could be compromised at G levels as low as 4 G with head rotation in the check-six position (34). Head rotation caused an increase in strain on these neck muscles by approximately 70% over extension: flexion positioning. Extension: flexion movements increased neck muscle strain by 270% compared to head movement in a neutral position.

Helleur et al. (59) developed a model of the neck that incorporated muscles and ligaments. They calculated the limits of supportable loads of these soft tissues for sustained G levels with the head in neutral, flexed, and extended positions. Rotated positions were not calculated. Using the data generated by Helleur et al (59), 30 G could be supported by the cervical spine in the neutral position, 25 G in head flexion, and 15 G in extension. On the other hand, when the G force was applied at an angle of 30 degrees to the head/neck in the extended position, (i.e., which might simulate a limited check six without head rotation) the region of supportable load before failure, was reduced to approximately 7 G. This G level would be reduced even more with the additional weight of the helmet. Also increased G exposures with the neck in a backward-

extended position can make cervical structural failure even more likely.

Snijders, et al. (116) developed a biomechanical model of the cervical spine examining the forces on several neck muscles during axial rotation, flexion, and lateral flexion. They examined 19 muscles of the neck. All head movements greater than 30° increased joint reaction and muscle forces significantly; e.g., the *splenius cervicis*, right and left, a major neck extensor muscle, increased forces from 40 N to 90 N going from 30° to 90° rotation. Neck extension was not considered nor was head rotation with extension calculated, but the addition of extension with rotation would be expected to increase neck muscle forces.

The foregoing information involves muscles and ligaments of the neck that are not fatigued. During sustained and repeated G exposures, muscle fatigue routinely occurs. Rates of fatigue for various neck muscles with various head loads and positions, at 70% MVC, have been measured (101). Fatigue of neck muscles occurred much more rapidly in the center high position with increased head weights (up to 4 kg) than other head positions. With head weights of 4 kg, which equates to a 3 G exposure for a 1.3 kg helmet, complete neck muscle fatigue at muscle contractions of 70% MVC occurred at 61 s. This represents an increase of 25% in rate of muscle fatigue over a 1G exposure. With 7 to 9 G exposures, the rate of fatigue would be expected to be even more rapid. Complete neck muscle fatigue, as measured in this study, substantially increases the chance of acute injuries and degenerative changes. But even with partial muscle fatigue, the spine is at increased risk. The head position of center high for this study is not completely relevant to the check-six position, which includes rotation that would be expected to further increase the rate of muscle fatigue.

Mertens (85) measured the stiffness and transmissibility of the body impedance during exposures to sustained G. The body and the vertebral spine stiffened significantly during exposures to sustained G, especially going from 1 to 2 G. Impedance was measured up to 4 G. Transmissibility of forces from the seat to the head increased dramatically. This increase in transmissibility of forces to the vertebra increases the risks of injury from repeated exposures to sustained G, especially subacute injuries that can accumulate over long periods of time and result in degenerative pathologies.

12.6.2 A Biomechanical Model for Calculating Loads on the Cervical Spine

The aim of the model was to quantify the external load effects on the cervical spine of pilots during increased G exposures. In accomplishing this task, the mass of the flight helmet and center-of-gravity locations on cervical spine were applied using MRI-determined sagittal moment arm length of the neck extensor muscles (57).

12.6.2.1 Methods

A fighter pilot's 1.14 kg helmet was equipped with Night Vision Goggles (NVG) weighing 0.761 kg. The question was whether adding a counterweight of 0.61 kg, aiming to move the center of gravity of the head-worn equipment backwards, would reduce the cervical spine load. The helmet and NVG induced a force of 21.4 N and with a counterweight 27.4 N. To determine the effects of high-G, the sagittal load on C₇-T₁ induced by the weight of the head-and-neck and by the helmet without NVG was also calculated for 1 G, 5 G, and 9 G. The weight of the head-and-neck induces a force of 7.9 % body weight (49). Other pilot-related biomechanical parameters are shown in Table 12-2.

Table 12-2. Pilot Related Biomechanical Parameters

Biomechanical Parameters	
Body Weight (kg)	78
Neutral Neck Position	10° flexed
Head and Neck:	
Distance c. g. ¹ to C ₇ -T ₁	150 mm
Weight Induced Force	60.45 N
Neck Extensors:	
Sagittal Moment Arm	37 mm
Muscle Strength	54 Nm

¹ c.g. = center of gravity

Adding a counterweight reduced the head-worn equipment center of gravity from 66 mm to 25 mm in a horizontal plane but increased the vertical distance 1mm (a) (Table 12-3). For research purposes a hypothetical reduction by 25 mm instead of 45 mm in the vertical direction, was also calculated (b).

Table 12-3. Distances for the different c.g. in relation to the head and neck, located in front of the ear (0; 0).

Equip. c. g. distance (mm)/relation to head c.g.			
Equipment		Vertical	Horizontal
Helmet + NVG		44	66
Helmet + NVG	(a)	45	25
+ Counterweight	(b)	20	25

These calculations did not take into account the additional weight of an oxygen mask that adds to the cervical spine load (55). As shown in Table 12-2 a body weight of 78 kg induced a force of 60.45 N from the head-and-neck. The cross-sectional area in the transverse plane of the muscles and the moment arms about the bilateral movement axis through vertebra C₆, were calculated to be 37 mm from a previous study (79). The sagittal distance from the head-and-neck center-of-gravity to C₇-T₁ was determined to be 150 mm. From our other studies, the mean neck muscle extensor strength in a group of fighter pilots was found to be 54 Nm, that was used in the present study (57). In a neutral position, the neck is already flexed 10 degrees in relation to the vertical plane.

These data were used in a model shown in Figure 12-9 that was developed for calculating cervical muscular load moment for 1 G in various flexion angles when using head-worn equipment of different masses (helmet only, helmet and night vision goggles, and counterweights at two locations). These different masses will also change the center-of-gravity locations (57).

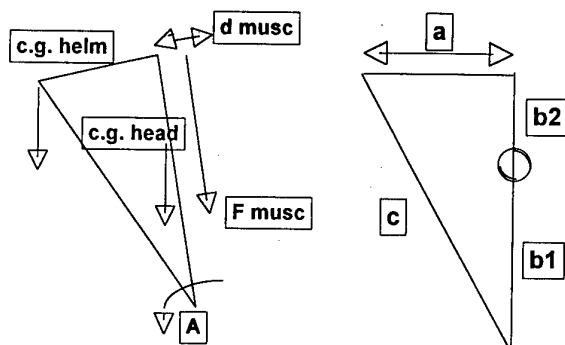


Figure 12-9. Biomechanical model used for calculations of sagittal plane, static cervical spine load. Left: A-bilateral axis for the cervico-thoracic motion segment C₇-T₁, center of gravity (c.g.) for the head-neck-neck (head) in front of tragus at the ear, and the head worn equipment (helm), respectively. Direction of compressive muscle force (F_{musc}) and its level (moment) arm (d_{musc}) is indicated. Right: Vertical distance from C₇-T₁ to c.g. head (b_1 , marked by a circle). Vertical distance from C₇-T₁ ($b_1 + b_2$) and horizontal distance (a) to c.g. helm c is the shortest distance between C₇-T₁ and c.g. helm.

12.6.2.2 Results

Figure 12-10 shows the summarized load moment of force (Nm) about a bilateral axis through the lower

cervical spine motion (C₇-T₁) of the equipment and the head-and-neck in different neck flexion angles at 1 G. Adding NVG-weight to the helmet substantially increased the load, especially when the neck is flexed. A counterweight decreased load moment, but only in the neutral or slightly flexed positions. Lowering the counterweight would be beneficial in flexed positions, but is of minor importance calculating the total load moment.

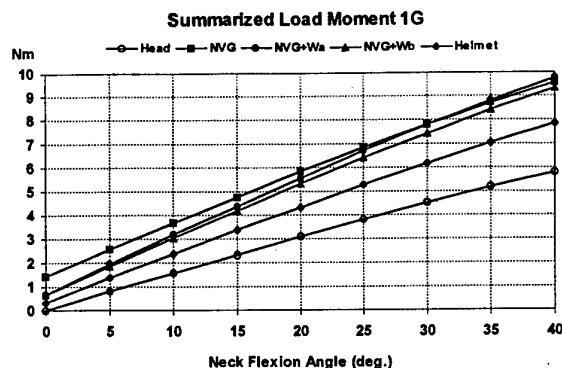


Figure 12-10. Sagittal load moment (force x lever arm, Nm) about the bilateral motion axis of C₇-T₁ induced by the mass of the head-and-neck (open circles) and summarized with that of helmet (filled diamonds), night vision goggles (NVG), NVG and counterweight (higher positioned; NVG + Wa), NVG and counterweight (lower positioned; NVG + Wb), respectively, at different neck flexion angles (deg) and 1 G.

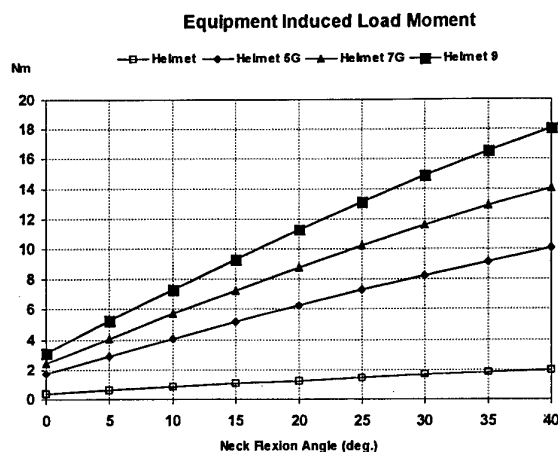


Figure 12-11. Sagittal load moment (Nm) about the bilateral motion axis of C₇-T₁ induced by only the mass of the helmet at different neck flexion angles (deg) for 1 G (open squares), 5 G (filled diamonds), 7 G (filled triangles) and 9 G (filled squares).

The helmet induced load moment alone at 1, 5, 7, and 9G are shown in Figure 12-11. The induced load moments for the head-and-neck and together with the helmet, respectively, are shown at 1 and 9 G in Figure 12-12.

The compressive force on the lower cervical spine C_7 due to the mass of the helmet and the head and neck in addition to the counteracting muscle forces is shown in Figure 12-13. The shear force (action being perpendicular to the compressive force) is shown in Figure 12-14. In a situation where NVG is used (not shown in the figure), it should be noted that due to the muscle force needed to counteract the external induced load moment, there was a positive effect by a counterweight in neutral and in flexed positions less than 15° . However, a counterweight increased the shear force, particularly in flexed neck positions. As the ligaments are not designed to counteract large shear forces in the neck; i.e., such forces must be taken seriously.

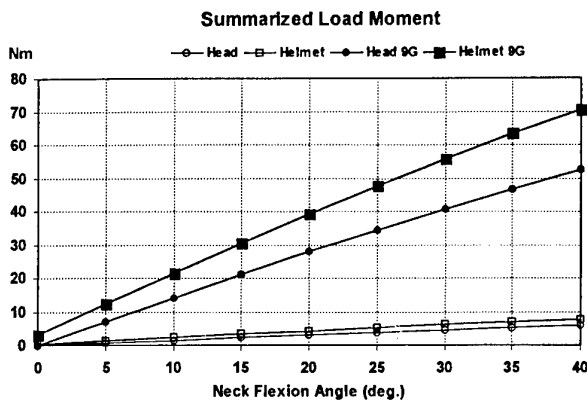


Figure 12-12. As in figure 12-11, but with the load moment (Nm) induced by the mass of head-and-neck (circles) and summarized with that of the helmet (squares); i.e., the load moment which the muscles and other structures need to counteract, in different neck flexion angles at 1 G (open symbols) and 9 G (filled circles).

The Muscular Strength Utilization ratio (MUR %) required in the neck muscles to counteract the induced load moment was calculated and is shown in Figure 12-15. The literature suggests that a continuous force of the muscles for more than one hour at 1 G_z should not exceed 5 % of their MVC. Also it is recommended that the work posture during the day should not exceed 15 degrees neck flexion (9). Our study showed, that being

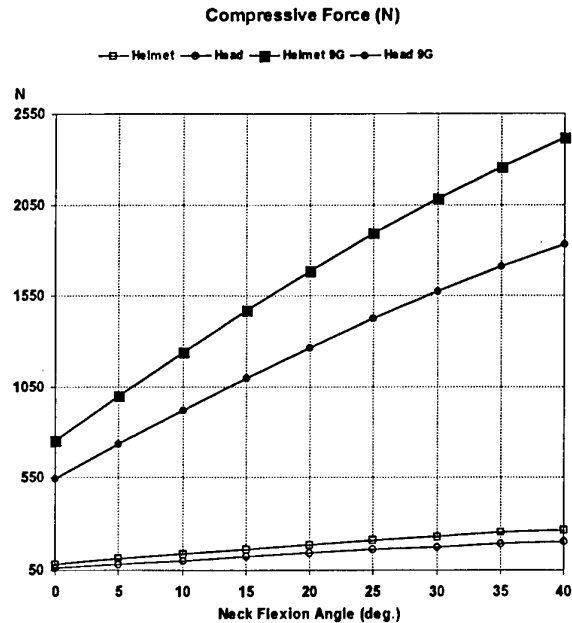


Figure 12-13. Cervical spine compressive forces (N), forces from counteracting neck extensor muscles included, due to induced load moments in Figure 12-12.

on a mission for one hour using helmet and NVG, which adds a total weight of more than 2 kg to the head, can only be performed with a 5° neck flexion without a counterweight and 10° with counterweight. We want to emphasize that these calculations are valid for 1 G and not for increased G levels (e.g. 9 or 12 G). Also besides the increased G effect, there is the additional complication of aircraft vibrations that will add mechanical forces on the neck structures.

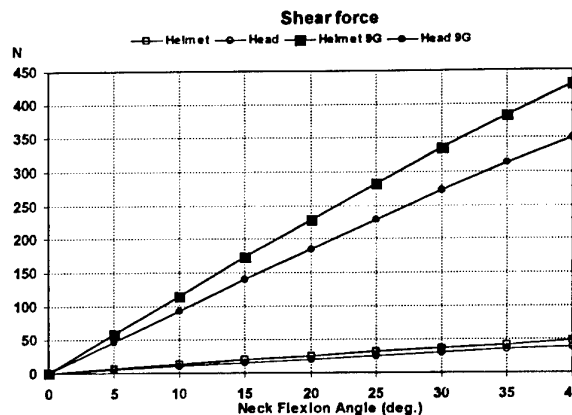


Figure 12-14. Cervical spine shear (i.e., perpendicular to the compressive forces, N), due to induced load moments in Figure 12-12.

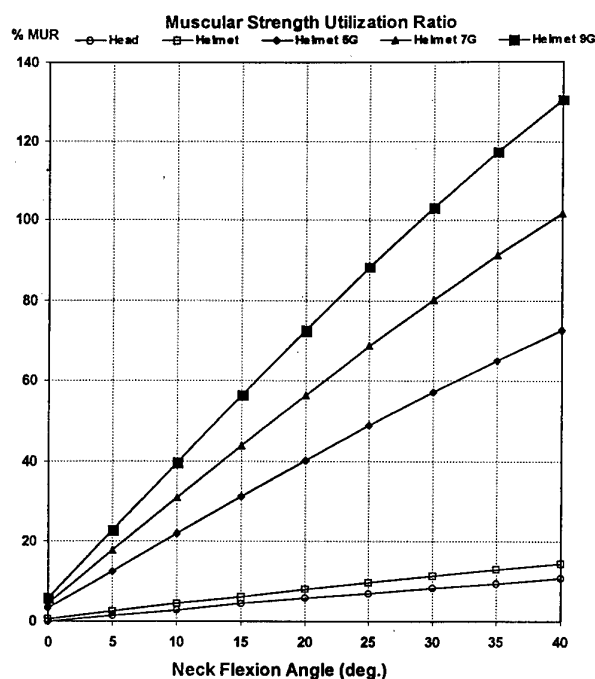


Figure 12-15. Percentage of neck extensor muscular strength (MVC; % MUR = work load/MCV x 100), with an assumed MVC of 54 Nm (54, 55) about the bilateral axis of C₇-T₁, needed to counteract the load moment induced by the head-and-neck only (open circles) at 1 G.

There is limited *in vivo* evidence in the literature about how flying an ACM in a high-G environment, with frequent turning and flexing/extending the neck, can cause acute and subacute vertebrae and disk injuries. Most studies are *in vitro* measurements and do not take into account the load from life support equipment. However, Helleur et al (59), in his modeling approach tried to calculate tolerances of the cervical spine to high acceleration with various head positions.

Using his model and the model developed herein, it seems clear that as long as the pilot has a healthy neck, is seated with the neck in an neutral position, and with G acting approximately along the axis of the cervical spine, the spinal forces are within tolerance limits. However, in flexed or extended neck positions with G acting more perpendicular to the spine, there are parts of the range of motion of the head where 9 G could cause spinal injuries. Of course with the additional weight of the head-worn life support equipment, the injury threshold is rapidly reduced. It is well known in sports medicine, that ligament and muscle injuries will increase the motion range of the head with instability

thus accelerating the degenerative joint processes of the cervical spine.

12.6.2.3 Summary

Our biomechanical calculations have shown that a pilot wearing 1.2 kg head equipment at 9 G_z with the head-and-neck in a neutral position induces a load corresponding to 60 kg on the top of the head at 1 G. Head movement that deviates from the neutral position will significantly increase muscle and joint loads in positions putting the structures of the cervical spine at greater risk. Adding weight to the helmet with night vision goggles substantially increased the load on the neck extensors. Counterweights, intended to shift the center of gravity dorsally, reduced the induced load moment. Indeed, due to the lower muscle force requirements, the total compressive force exerted by muscles, body segments and the weight of the equipment was reduced. However this effect was decreased with an increased neck flexion angle. Also the shear forces increased with added counterweight and flexion angle.

12.6.2.4 Conclusion

Any addition to helmet weight must be treated with caution because of the risks of injury in sustained neck flexed and rotated positions. Also increased helmet weight adds to the risk of serious neck injury by far exceeding neck structural strength limits in the event a pilot ejects.

CHAPTER 13

META-ANALYSIS OF STUDIES ON CERVICAL DEGENERATION OF FIGHTER PILOTS

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13.1 INTRODUCTION

Descriptions and separate analyses of many studies considered in this AR have been reviewed. Clearly there are compelling data that demonstrate a causal effect of exposures to sustained G on acute cervical injuries. These injuries include frequent muscle injuries as well as injuries involving ligaments, vertebrae, and vertebral disks. In addition there is considerable evidence from several of these studies that repeated exposures to sustained G over the lifetime of a pilot may accelerate degenerative changes of the cervical spine. Unfortunately, these studies are less compelling since they usually involve small numbers of pilots, degenerative changes have several criteria and frequently without symptoms and too increasing age causes the same types of pathologies. These studies were conducted by different nations using different protocols. However there are many similarities in the results with these studies that will allow a statistical comparison. Therefore the use of meta-analysis was considered appropriate for these separate studies to test their combined statistical significance and increase the power of the comparative results.

Meta-analysis is a quantitative analysis of two or more independent studies. This type of statistical analysis integrates data from these studies, providing a probability value of a sustained-G exposure effect. The power of this analysis is that it is able to significantly increase the number of subjects by combining all of the subjects in these studies. The weakness of this analysis is that each study has some differences in their protocols that dilute the significance resulting from the greater numbers of subjects (58).

Some of the many differences among the studies used in my analysis include selection of subjects, ages of subjects, hours of flying time of high performance aircraft, aircraft used, pilot flight and physical training, personal equipment, cockpit design, flying conditions, diagnostic procedures, lifestyles, and experimental

design of the study (cross-sectional, longitudinal, retrospective, prospective). On the other hand several of the above items that had differences also had sufficient similarities. These similarities provided useful data so that a meta-analysis could be performed using several of the studies described in this report.

13.2 METHODS

The data used in the meta-analysis came from the following control studies. The numbers used with the following studies are used as identification of those studies in Tables 13-1; 13-2; and, 13-4.

13.2.1 Selection of Studies

1. Degeneration of cervical intervertebral disks in fighter pilots frequently exposed to high +Gz forces. Hamalainen, O., Vanharanta, H., Kuusela, T.
2. Cervical spine degeneration effects of fighter pilots. Petren-Mallmin, M. and Linder, J. - Chapter 11.
3. Degenerative changes of the spine of fighter pilots of the Royal Netherlands Air Force (RNLAf). Hendriksen, I. And Holewijn, M. - Chapter 4.
4. Radiological evaluation of the cervical spine of high performance aircraft pilots. of the Spanish Air Force (SPAF). Rios-Tejada, F., Herrera, M., Garcia, J. A., Garrido, J. V., Diaz, C. V. - Chapter 5.
5. Comparative study of F-1 and F-15 pilots' spines by MRI in the Japanese Air Self Defense Force. Tachibana, S. and Hanada, R. - Chapter 7.
6. Progressive cervical osteoarthritis in high performance aircraft pilots. Gillen, M. H. and Raymond, D.

7. Spinal injury in Turkish Fighter Pilots. Turbedar, E., Yilmaz, U., Alan, M., Buyukcakil, C., Sarilayalar, U., Savasan, M. - Chapter 6.

8. Analysis of radiographic screening of fighter pilots' cervical vertebrae. Ziyan, W., Lu Qijiu, Li Zhu

13.2.2 Selection of Data for Meta-Analysis

The results from each of the studies were evaluated and validated by two reviewers. Information was extracted from each study, such as total sample size, number of pilots exposed to high-G, number of controls, and the p-value associated with the comparison of the rates of degeneration of the spine for the two groups. Discrepancies between reviewers were evaluated and resolved. Authors were contacted as necessary to verify some of the published data. Chi-Square analyses were performed to validate the published p-values.

Table 13-1 lists each study numbered 1-8 as noted above, the total number of subjects in each study, and the results of a significance test of rate differences between the subjects exposed to high G forces and the control group for each study. These values were used in the meta-analysis. One composite p-value was used for each study even though the authors may have reported summary statistics from many measurements. The age ranges of the subjects of each study are also shown. A brief description of the study design and the diagnosis method is listed for comparison purposes.

Table 13-2 summarizes the studies in more detail. The number of pilots exposed to high G forces and the percentage diagnosed with degeneration of the cervical spine are listed along with the number of controls and their percentage of degeneration. The difference in the rate of degeneration between the two groups for each study is also shown along with the upper and lower 95% confidence interval (CI). A summary of all eight

studies is displayed on the last line of the table. Over all of the studies, 29% of the pilots that were exposed to sustained G were diagnosed with degeneration of the cervical spine compared to 15% of the controls diagnosed with degeneration. Study 6 was omitted from these calculations since the information was not available.

Various meta-analytic strategies have been developed. For this meta-analysis, individual significance tests from a number of studies were combined into one overall pooled test. Each individual probability was converted to a Z score, and these Z scores were summed across all studies. This sum was divided by the square root of the number of tests combined. The results were back-transformed into an overall p-value. The advantage of such a procedure lies in the increased power of the overall comparison.

Variations in study outcomes were assessed by a test of homogeneity. Are the studies estimating the same effect, after considering possible bias and confounding in each study? Also a sensitivity analysis was performed to determine the extent to which inferences depend on a particular study.

In looking at the influence of each study, meta-analysis was repeated one at a time without each study. If there is little change in inference without the study, then inclusion of the study cannot produce serious difficulties, even if unquantified biases exist in the study. The results of a meta-analysis may be biased if the studies included are a biased sample of studies in general; for example where there is a tendency for papers that report an association to be preferentially published over those that report no association. This bias is addressed also. An effect size 'r' is obtained as an estimate of the magnitude of the difference between the rates of degeneration of the cervical spine between

Table 13-1 Description of each study used in the meta-analysis calculations

Ref	N ¹	P-value ²	Age ³	Age ⁴	Study Design	DX Method
1	23	0.739	35-37 yrs	35-37 yrs	Exposed vs age/sex-match controls	MRI
2	31	0.026	28-49 yrs	32-48 yrs	Exposed vs age-matched controls	MRI
3	307	0.013	17-49 yrs	16-48 yrs	F-16 pilots vs controls	X-ray twice
4	48	0.281	31.4 yrs ⁵	32.5 yrs ⁵	Fighter pilot vs cargo pilots	X-ray/MRI
5	80	0.444	28.2 yrs ⁵	29.0 yrs ⁵	F-15 vs F-1	MRI
6	44	0.050	23-55 yrs	24-55 yrs	Exposed vs age/sex-match controls	X-ray
7	470	0.202	unknown	unknown	F-16 vs Other Pilots	X-ray
8	178	0.002	26-35 yrs	26-35 yrs	Fighter pilots vs ground crew	X-ray

¹ Sample size; ² (right tail); ³ Exposed group (age range); ⁴ Control group (age range); ⁵ mean age

Table 13-2. Summary of the data from each study used in meta-analysis

Ref No.	N ¹	N ²	N ³	% Positive ²	% Positive ³	Rate Diff	Lower 95%CI ⁴	Upper 95%CI ⁴
1	23	12	11	91.7% (11)	90.9% (10)	0.008	-0.223	0.238
2	31	16	15	31.2% (5)	0% (0)	0.312	0.085	0.540
3	307	186	121	15.6% (29)	6.6% (8)	0.090	0.021	0.158
4	48	24	24	50.0% (12)	37.5% (9)	0.125	-0.153	0.403
5	80	32	48	43.8% (14)	39.6% (19)	0.042	-0.179	0.262
6	44	31	13					
7	470	91	379	14.3% (13)	10.6% (40)	0.037	-0.041	0.116
8	178	116	62	47.4% (55)	22.6% (14)	0.246	0.110	0.386
TOTAL	1181	508	673	29.1% (139/477)	15.2% (100/660)	0.139	0.091	0.189

¹ Total sample size; ² G Exposed; ³ Not G exposed; ⁴ Confidence Interval

subjects that fly high performance aircraft (sustain high G) and a control group that does not sustain high G.

13.3 META-ANALYSIS RESULTS

Meta-analysis using 'Combining Probabilities or Significant Tests' was used in these analyses (105). The results of the combination of the probabilities of the eight studies using a meta-analysis are shown in Table 13.3

Table 13.3 Meta-analysis results of 8 studies

Meta-analysis	n ¹	P-value< (one tail)	Effect size r	Test of Homog ²	Fail ³ Safe N
Unweighted	1181	0.001	0.099		
Weighted	1181	0.002	0.085	0.209	26 ³

¹ Sample size; ² Homogeneity; ³ P = 0.05

Combining the probabilities of these eight studies leads to a significant result ($P = 0.002$) indicating the small likelihood that there is no difference in the rates of degeneration between the two groups. Although four of the studies were not significant, the null hypothesis can be rejected for all eight studies combined. The unweighted results are given in order to compare the results with the population rates of Table 13.2.

The results of the Chi-Square test of homogeneity are not significant indicating that the eight studies are homogeneous and there is no evidence that the eight studies should not be combined. The 'Fail-Safe N' reflects the number of non-significant 'file drawer studies' necessary to invalidate the significant overall

significant findings would be required to bring the overall p-value of 0.002 above the 0.05 level.

13.3.1 Sensitivity Analysis Results

A sensitivity analysis was performed to determine the extent to which inferences depend on a particular study. In looking at the influence of each study, the meta-analysis was repeated one at a time without each study. If there is little change in inference without the study, then inclusion of the study cannot produce serious difficulties, even if unquantified biases exist in the study. The sensitivity analysis was performed using meta-analysis 8 times with only 7 of the studies included each time (133). The results are listed in Table 13.4. Thus for the first line of the table, study 1 was omitted and studies 2 through 8 were included in the meta-analysis. The results are very similar for the unweighted analysis (each study weighted equally) and the weighted analysis (weighted by the size of the sample). The results of the meta-analysis do not appear to depend upon any one study.

13.4 SUMMARY AND CONCLUSIONS

The meta-analysis is consistent with a positive association between exposure to sustained G and degenerative changes in the cervical spine. Aircrew members that fly high performance aircraft have an increased probability of developing degenerative changes in the cervical spine than age-matched-control subjects that are not exposed to increased sustained G.

Table 13.4. Sensitivity analysis of the meta-analysis calculations

Meta-analysis without each study	N ³	P-value (one tail) ¹	Effect size	P-value (one tail) ²	Effect Size	Test of Homogeneity	Fail ⁴ Safe N
1	1158	<0.001	0.114	0.002	0.086	0.448	32
2	1150	0.002	0.085	0.002	0.083	0.172	15
3	874	0.003	0.094	0.020	0.070	0.207	13
4	1133	<0.001	0.101	0.002	0.085	0.162	23
5	1101	<0.001	0.108	0.002	0.088	0.213	26
6	1137	0.001	0.089	0.003	0.083	0.151	16
7	711	<0.001	0.124	0.001	0.137	0.148	21
8	1003	0.005	0.080	0.016	0.068	0.376	10

¹ Unweighted; ² Unweighted; ³ Sample size; ⁴ (P = 0.05)

CHAPTER 14

SUMMARY AND CONCLUSIONS

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14.1 INTRODUCTION

This TW began as a survey of information that had been developed from scientific/medical publications, technology reports, and anecdotal sources. However it became clear that even though this information was important in understanding more about cervical spinal injury and diseases, it was limited to increasing our knowledge base regarding what, when, and where this was occurring, and it didn't address the why and the how. The why and how are what we most need to understand if we are to have an affect on this occupational hazard.

What is defined as the acute neck injuries of soft and hard tissues and cervical degenerative changes. When these lesions occurred is during sustained G exposures and age of the pilots is a contributing factor. Where these lesions occurred is primarily in the cervical region affecting specific cervical vertebrae and disks. However to put these findings into proper perspective, the why and how had to be determined. These were addressed in Chapter 12.

Why this occurs is because of the structure of the cervical spine, the direct relationships between the soft tissues (muscles, ligaments, joint capsule) and the vertebrae, and head positions of the pilot during sustained G exposures. How this occurs is related to the external load of G, the occurrence of fatigue, and injury to the soft tissues, which increase external trauma on the vertebrae and disks, which in turn produce degenerative changes.

14.2 BIOMECHANICS OF THE CERVICAL SPINE WITH SUSTAINED G

The cervical spine in a neutral position is capable of supporting large external loads. However pilots of high performance aircraft during ACM frequently have their head positioned in a rotated extended "check six" position. This position, because of high load moments of force, places cervical muscles, ligaments and spine at increased risk for acute injury. Since muscles and

ligaments are the primary support structures for intervertebral disks, once injured they significantly increase the risk of subacute and acute spinal injuries. The ACM environment develops forces that are sufficient to cause: (1) acute muscle and ligament (soft tissue) injury; (2) acute vertebrae and disk (hard tissue injuries); and (3) chronic injury (degeneration of the spine).

14.3 MECHANISMS OF DEGENERATION OF THE SPINE WITH SUSTAINED G

Degeneration of the spine principally involves disk injury and degeneration with the development of osteophytes (spondylosis). The former apparently occurs first and initiates the development of osteophytes that may provide support to the spine. Numerous instances of acute intervertebral disk injuries associated with increased sustained G have been documented. Therefore subacute injuries of these disks must be common occurrences. Physiologic increased external loads that are sustained for only a week, produce early degenerative changes in vertebral disks in mice. The ACM environment produces external loads that could produce these types of pathologies. Consequently repeated exposures to these external loads with sustained G over several years could well lead to the acceleration of spinal degeneration.

14.4 OCCURRENCE OF CERVICAL INJURIES

14.4.1 Acute Soft Tissue Injuries

Acute neck injuries of fighter pilots are commonly reported by surveys of Air Forces of many nations. These surveys show that the majority of pilots flying high performance aircraft frequently suffer acute neck injuries. These neck injuries usually occur when pilots have their head rotated and extended in "check six" position or while rotating their head during exposures to G and can be serious enough to ground the pilot. Check six is an unstable head position requiring major muscle and ligament activities that places the neck at increased risk because of the large load moments. Consequently

acute injuries occur that involve the muscles and ligaments of the neck which support the head and cervical spine. Injuries to cervical ligaments were documented during exposures to high-sustained G. These ligament injuries have occurred at the C₅, C₆, and C₇ vertebrae. This condition has been modeled for the lumbar spine (should be the same or worse for the cervical spine), showing that ligament injuries result in destabilization that substantially increases the risk of damage to the disks (71).

The principal muscles involved during increased G exposures are the neck extensors of which the *cervical erector spinae* is a major player. Hamalainen and Vanharanta (34) have shown that during sustained exposures of 7 G, this muscle commonly reaches its maximum voluntary contraction (MVC) capability. During head rotation, 100% MVC can be reached as low as 4 G. Consequently it is not surprising that acute neck injury is a common occurrence among fighter pilots who routinely experience even moderate levels on a daily basis. Also pilots may assume a head position for extended periods of time that involves extension of the upper neck and flexion of the lower neck (Figure 12-3). This static head position is used for hours as they fly cross-country and prior to ACM engagements. This position develops a high load moment of force on the lower neck. Consequently this position will fatigue important cervical muscles and may contribute to neck injuries during ACM.

Acute soft tissue injuries identified by neck pain was correlated with degenerative changes as found in two studies (Chapter 7, 138) and one clinical report (86).

14.4.2 Acute Hard Tissue (Spinal) Injuries

Table 14-1: Nature and Location of Spinal Injuries

C ₃₋₄	C ₅	C ₅₋₆	C ₆	C ₆₋₇	C ₇	G Level	Ref
	C.F. ¹					9	108
					C.F.	6.5	108
					F.S.P. ²	5	108
			C.F.			8	6
		H.D. ³				8.4	108
				H.D.		9	108
H.D.						?	19
				H.D.		7	86
				H.D.		5	86
H.D.		H.D.		H.D.		6.7-7.2 G	38
				H.D.		4	90

¹ Compression Fracture; ² Fractured Spinous Process; ³ Herniated Disk/Protrusion/Bulging

These surveys of acute neck injuries conclude that their findings are important since they document a significant impact on operational readiness. While that is true, these injuries also place the neck at higher risk for more serious acute cervical spinal injuries as well as possibly begin the process of spinal degeneration. It is generally acknowledged that the initial defense in protecting the cervical spine against spinal disk injury is the soft tissues of the neck; i.e. muscles and ligaments. Consequently, the occurrence of neck soft tissue overload (surpassing maximum recommended % MVC of 70 %) with or without injury, places the cervical spine at risk for acute injuries of the vertebrae and disks. Various types of acute hard tissue spinal damage during exposures to operational levels of sustained G have been documented. The types and sites of these injuries are shown in Table 14-1.

Table 14-1 shows that two types of spinal injuries occur: (1) fractures of the vertebrae and (2) disk herniation or protrusion. Generally, these fractures are located at C₅, C₇ and the disk injuries involve the same vertebrae. These injury sites coincide with apexes of angles of neck hyperflexion and hyperextension. Also the locations of these injuries coincide with increased degenerative changes of necks of pilots (as shown in Table 14-2) and with aging. C₆₋₇ is by far the most commonly affected intervertebral space. This joint does not have the maximum mobility nor is it the site of the apex of the angle for hyperextension or hyperflexion. But it is located closest to the site of the apex of the angle of hyperflexion (C₅ and C₆). Hyperflexion can occur during increased G exposure; i.e., pilots find that their heads are forced down onto their chest with the high G, remaining in that position until the G is reduced. This extreme hyperflexion with high G may very well lower

Table 14-2: Type and sites of cervical spine degenerative changes associated with sustained G

C ₃₋₄	C ₄	C ₄₋₅	C ₅	C ₅₋₆	C ₆	C ₆₋₇	References
		N ¹	O ²	N	O		31
D ³		D		D		D	37
DP/N ⁴	O&I ⁵	DP/N	O&I	DP/N	O&I	DP/N	99
		O				O	Chapter 4
D		D	I ⁵	D	I		Chapter 5

¹ Disk Narrowing; ² Osteophytes; ³ Disk Degeneration; ⁴ Disk Protrusion and Narrowing;

⁵ Vertebral Body Signal Intensity

the site of the hyperflexion apex of angle found at 1 G by one intervertebral space to C₆₋₇.

It is of interest that several of these hard tissue injuries occurred at moderate G levels; e.g. 4 and 5 G. The question arises, since many of these injuries occur at lower G levels, why has the incidence rate apparently increased with higher G aircraft? Probably the reason is the greatly increased incidence rate of acute soft tissue injuries that commonly occur with exposures to higher G levels. Soft tissue injuries involving ligaments of the neck were documented with these hard tissue injuries on two occasions (6, 90). Incidentally many of these injuries also occurred with head rotation or in the check six position as commonly found with acute soft tissue neck injuries.

The nature, location, and G levels where these hard tissue injuries occur support the notion that acute tissue overload due to exposures to high G, head rotation, flexion or fatigue are involved. Thus they appear to be an important predisposing factor.

14.5 OCCURRENCE OF SPINAL DEGENERATION

This TR reported on several published articles on the occurrence of degenerative disease of the spine. These reports found similar lesions involving the same cervical vertebrae and disks. In addition, three studies that originated from this TW also focused on degenerative diseases of the cervical spine. The nature and site of degenerative changes of the cervical spine are shown in Table 14-2.

These data in Table 14-2 are from 284 fighter pilots and 192 age and sex matched controls without G exposure. These numbers represent a relatively large experimental population of pilots from different nations involving various aircraft. All of these data represent similar degenerative changes of the same regions of the cervical

spine; i.e., regions expected to be involved with this type of disease. Indeed, these cervical regions are generally involved with aging, maximum neck flexion and extension, and acute injuries of the soft and hard tissues of the neck.

Other reports and studies that did not report on specific vertebral sites also reported increased incidences of degeneration of the cervical spine in pilots exposed to sustained G. Chapter 6 (Turkey) reported increased degenerative changes of the cervical spine of 91 F-16 pilots (72% that had spinal lesions compared with 48% for pilots of lower G aircraft). These changes included herniated disks and spondylosis. Chapter 7 (Japan) found increased neck pain in F-15 pilots that was associated with increased disk degenerative changes compared to lower G pilots. These degenerative changes involved the disks.

Two longitudinal studies were reported in this TR; i.e., chapters 4 and 11. Also, Hamalainen et al (42) have an ongoing study that is longitudinal. The study reported in chapter 4 is retrospective. The longitudinal study reported in Chapter 11 is prospective. Chapters 5, 6 and 10 reported on cross-sectional studies. The merits of each type of study is debatable although a well-planned (prospective) longitudinal study probably provides the most reliable data; e.g., Chapter 11. Petren-Mallmin and Linder (Chapter 11) found that the increase in degenerative changes associated with repeated increased G exposure disappeared as the same pilots and controls aged; i.e., the rate of increase was the same for both groups of subjects (Figure 14-2).

In that regard it is interesting that Gillen and Raymond (31) also noted an acceleration of degenerative changes of the cervical spine in young pilots. Also, Poland showed the greatest reductions in spinal mobility in fighter pilots 30 – 40 years of age. Younger and older low-G pilots had spinal mobility similar to the fighter pilots. Ziyen et al (1998) concluded that the 'degree of cervical vertebrae degeneration is related to pilots' age

and total flying hours.' Since they studied fighter pilots, 'total flying time' would be directly related to total time at increased sustained G levels.

14.5.1 Meta-Analysis of Spinal Degeneration Studies Related to Sustained G

Data from eight published articles and studies reported herein were analyzed using meta-analysis (Chapter 13). All studies that could be analyzed using this type of analysis were included regardless of their results. That analysis found that with a very high level of probability of $P < 0.001$ (unweighted) and $P < 0.002$ (weighted), these studies when combined showed that degenerative spinal disease occurred more commonly in fighter pilots than in age-matched non- or low-G controls. To put this significance in proper perspective, 26 non-significant 'file drawer studies' would be necessary ('Fail-Safe N') to invalidate the significant overall result at the $P = 0.05$ level.

14.6 CERVICAL SPINAL DEGENERATION ASSOCIATED WITH SUSTAINED G EXPOSURES

Degeneration of the cervical spine occurs normally with increasing age. The onset of cervical spinal degeneration occurs towards the end of the second decade of life, accelerates during the fourth and fifth decades and slows thereafter. This age function is qualitatively sigmoidal. A major reason for the occurrence of spinal degeneration with increasing age is because of the persistent external load of gravity. The force of gravity is continuous and pervasive throughout a lifetime of a human using an erect posture. With the occurrence of osteoporosis of vertebrae, their specific load increases thus stimulating osteophytosis. The formation of osteophytes is considered a form of spinal degeneration but since it increases the strength of the spine, it may also be considered an anatomical adaptation (89). Because it is a natural occurring phenomenon in all individuals with variable rates of progression, it is extremely difficult to measure changes in its rate of progression. The question remains - do repeated exposures to increased external loads in the form of increased sustained G increase the rate of onset of cervical spinal degeneration?

Most studies have shown that degenerative changes of the cervical spine occur more much commonly in fighter pilots than low-G age matched controls. Meta-analysis of all of these studies (Chapter 13) bears out these findings with a $P < 0.001$. Statistically it appears that there is a causal relationships between repeated exposure to G and degenerative changes of the cervical spine.

14.6.1 Relationship Between Acute Neck Injury and Spinal Degeneration

The sustained G environment provides increased external loads that have been shown in mice to accelerate spinal degeneration (80). These increased forces, according to our model, are capable of causing subacute injuries to intervertebral disks of the cervical spine. Certainly as shown throughout this TR, acute injuries of soft and hard tissues of the neck have been documented as commonly occurring during exposure to increased sustained G. Acute neck injuries have been linked with degenerative changes (Chapter 7, 86, 138). Therefore it is reasonable to assume that these types of injuries lead to spinal disk injuries that initiate degeneration of the spine (Figure 14-1).

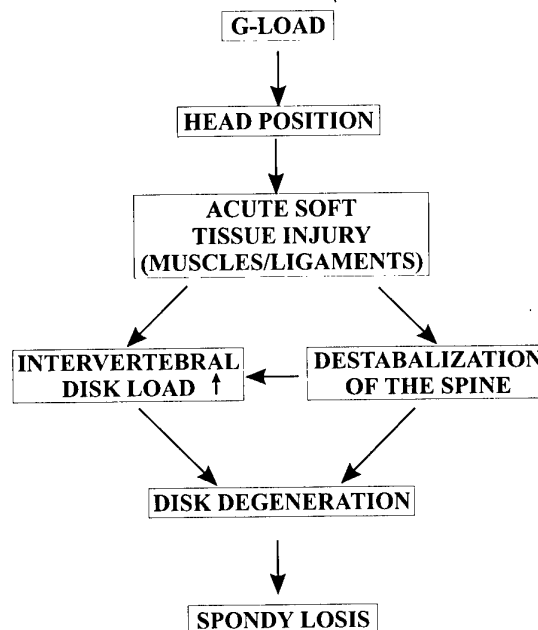


Figure 14-1: Model of the relationship of the development of spinal degeneration with acute soft tissue neck injury.

However the role of age in this process is an important factor that must be considered in the cervical degeneration model that follows.

14.6.2 Theoretical Relationship between Aging, Repeated Sustained G and Spinal Degeneration

Degeneration of the spine due to repeated G loading appears to occur with subacute lesions of the intervertebral disk. These lesions occur naturally and more frequently at 1 G with increasing age. It is logical to conclude that if the external loading is increased, as

with repeated increased sustained G exposures, spinal degeneration will occur at a younger age. This concept is shown graphically in Figure 14-2.

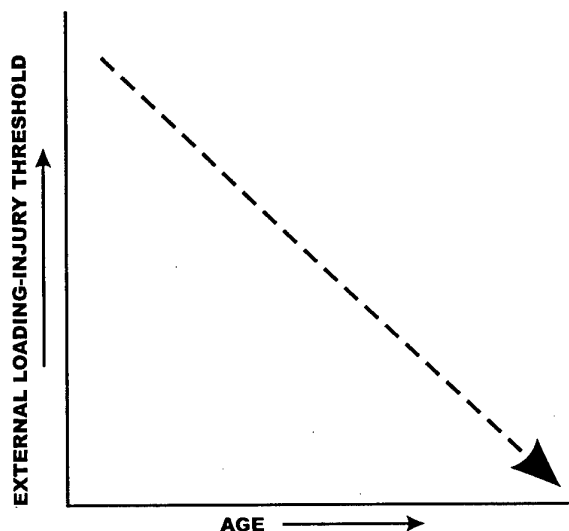


Figure 14-2: Relationship between external loading on cervical injury threshold and age. Increased levels of loading will cause cervical injury at a younger age.

Degeneration of the spine is a combination of degenerative lesions of the intervertebral disks and growth of bone mass (development of osteophytes). The latter increases the supporting structure of the spine so that it is not entirely a deterioration of the spine but can be considered as a form of adaptation to increased specific loads (89). Stupakov et al (Chapter 8) also noted the occurrence and importance of adaptive bony changes in higher G pilots. Increased osteophyte formation is known to occur in fighter pilots and increase with age and exposure to increased G (Tables 11-1; 14-2).

Elimination of these loads occurs when pilots reduce their time or stop flying high performance aircraft and reduce the stimulus for the development of osteophytes. At this stage of G-induced spinal degeneration, the spine has developed excess bone mass and strength for the 1 G environment. This is perhaps the adaptation of the spine that results in an increase in biomechanical strength that Stupakov et al (Chapter 8) describes.

Thus spinal degeneration is slowed or perhaps even stopped when high G exposure ceases. This reduction in the rate of spinal degeneration may be only temporary, since the process of aging will eventually

stimulate further osteophyte growth. Yet, the resumption of osteophytosis depends upon the age of the person involved since in the fifth and sixth decades of life, the development of cervical degeneration tends to decrease (61, 89). Osteophyte growth is stimulated with increasing age because of increased deterioration of the intervertebral disks and weakening of vertebrae which occurs with age-related osteoporosis.

Presumably, cervical degeneration results from repeated exposures to sustained G that occurs during the earlier years of flying. The relationship of G related pathologic changes of the cervical spine can be determined using the data of Petren-Mallmin and Linder in Chapter 11. The results of their 5 year study of different age groups of pilots and an age control group is shown in Figure 14-2.

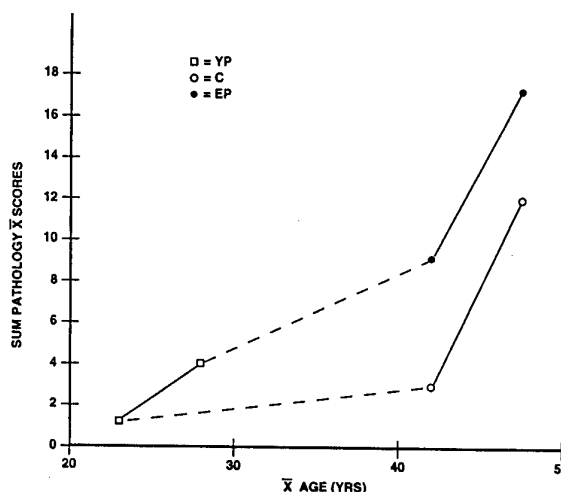


Figure 14-3: Relationship of age (yrs) with the development of cervical spinal degeneration. YP = young pilots; C = controls; EP = experienced pilots.

In Figure 14-3, the continuous lines connect data determined in their study. The dash lines span years of age outside of the ages considered by that study. The youngest YP group at 23 years of age that includes pilots with little flying time (220 hrs) can serve as a baseline for cervical spinal pathologies in young men for their three groups. Following the slope of the increase in cervical spine pathologies of YP, the rate of increase in cervical degeneration in pilots, up to 42 yrs of age, is rectilinear. A qualitatively similar rate of increase is found for C, but is considerably lower up to that age, thus indicating a significant sustained-G effect. However in both the C and EP groups, the rate of increase in cervical pathologies is accelerated and

similar for both groups at ages > 42 yrs of age; i.e., the G effect now appears to be diminished or even absent. It is clear that an age effect has become dominant for both groups. Theoretically then, later in life (60 yrs of age?) cervical spines of fighter pilots are at the same stage of degeneration as people who have never been exposed to increased-sustained G. A schema of a model that shows how this process might occur is shown in Figure 14-4.

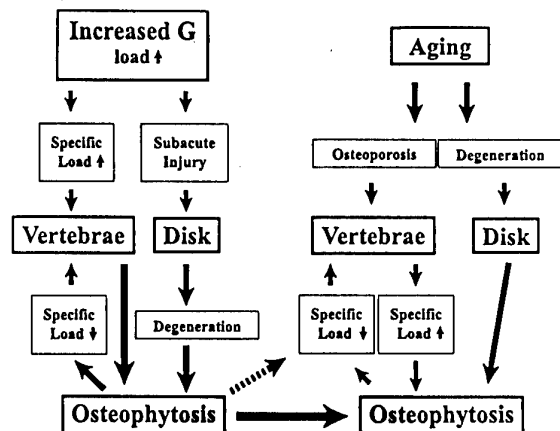


Figure 14-4: Schema of a model of cervical spine degeneration from repeated exposures to sustained G as it relates to natural spinal degeneration with aging.

14.7 CURRENT APPROACHES TO PREVENTION

Several nations now use various approaches in attempting to prevent or at least reduce the occurrence and operational impact of acute and chronic neck injuries in fighter pilots. These activities have been developed because of the concern that these pilots have an increased risk of acute neck injury and cervical degeneration.

The most common method used by most nations involves physical activities and conditioning. These activities generally involve encouraging their pilots to increase muscle strength of their entire body, with emphasis on neck muscles. Unfortunately an exercise regimen for neck muscles that is specific for the fighter pilot environment has not been developed that will produce balanced neck support.

Pilots are also encouraged to warm up their neck muscles prior to engaging in ACM exercises. Once engaged in sustained G activities > 4G, pilots are instructed not to move their heads. All pilots are also keenly aware of the dangers to another crewmember of unexpected rapid-onset increased G maneuvers.

Some nations have pilot-candidate selection programs that involve medical and physical criteria that are related to the neck. These include spinal screening using MRI or X-ray and family and medical histories.

Poland is instituting several initiatives in the treatment of neck injuries that should be considered by other nations. These include providing flight surgeons with a greater awareness of the problem that includes the recommendation of specific aggressive treatment regimens. Certainly neck pain is not a trivial problem for fighter pilots as it may well lead to more serious conditions including the initiation of degenerative conditions of the cervical spine.

All nations are aware of the problems caused by increased weight of head-mounted equipment. Although these problems are most appropriately concerned with pilot performance, their impact on acute and chronic neck injuries should not be underestimated.

14.8 CONCLUSION

The task of the Technology Watch (TW) on 'Spinal Injury from Repeated Exposures to Sustained G' was aimed primarily at the cervical spine with special consideration to be given to degenerative changes. Acute spinal injuries directly related to exposures to increased G have been well documented for several years, but the effects of repeated exposures on the spine that cause subacute injuries are less obvious and were therefore the focus of this TW.

It was obvious from the beginning of the TW, however, that acute injuries of the cervical spine would be related to the process of spinal degeneration. Acute injuries of neck muscles and ligaments, intervertebral disks, and vertebrae have been well documented and this information was reviewed in Chapter 2. Degenerative changes of the cervical spine were documented and related to acute changes discussed in Chapter 3 (Figure 14-1). A relationship was established that associated similar sites of injury and degeneration.

The following 7 chapters reviewed information from several countries concerning their experiences on this subject. Four of those countries conducted controlled studies of fighter pilots. All 7 chapters reported on increased cervical spinal injuries and/or degenerative changes of pilots routinely exposed to higher levels of sustained G. The prospective longitudinal study, reported in Chapter 11, found a sustained-G relationship with age and cervical degeneration (Figure 14-3). Meta-analysis confirmed that these studies did indeed have

similar results and valid conclusions with a $P < 0.001$; i.e., cervical spinal degeneration is directly related to exposures to sustained G (Chapter 13).

A review of information on the biomechanics (Chapter 12) of the spine and a model developed herein on that topic found that increased G provided sufficient force to cause acute injuries and initiate degenerative changes. An animal model established the process where sustained increased loads on the spine of an animal initiated degenerative changes within one week of exposure. Another animal model showed that acute injury to the disk annulus initiated degeneration of the nucleus pulposus even though the annulus lesion had healed.

Cervical spinal degeneration naturally occurs with increasing age. This age relationship probably happens because as the intervertebral disks age, they lose their elasticity, thus becoming more susceptible to subacute injuries that initiate disk (spinal) degeneration (Figure 14-2). Therefore it is concluded that repeated exposures to increased G initially accelerate this aging process. On the other hand, the rate of this aging process in pilots may return to a normal rate later in life (Chapter 11). A model was developed that describes this process (Figure 14-4).

In conclusion, repeated exposures to sustained higher levels of G can cause serious acute injuries to the cervical spine that will affect mission readiness. Also exposures to G appear to accelerate the normal aging process of spinal degeneration. Although the negative impact of the cervical spinal injuries examined herein on flight operations as a whole, appears to be minimal, it has potentially serious implications for the health of some pilots. Additional information is necessary to fully understand the relationships of repeated exposures to sustained G with cervical spine degeneration, but it is clear from the information presented herein that preventive measures to protect the neck are warranted.

CHAPTER 15

RECOMMENDATIONS

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15.1 INTRODUCTION

Writing this Technical Report provides an excellent opportunity to develop recommendations that focus on relevant issues. In this TR, information was obtained through literature searches, scientists networking (i.e., personal communication) and with four ongoing studies. These studies added considerable new data to the knowledge base. In that regard there is information in this TR that has yet to be published. Therefore this TR has probably advanced the knowledge base farther than most reports.

The recommendations that follow are based entirely on information that is presented herein. Therefore the serious reader is advised to carefully review the entire TR, to develop an appreciation for how the conclusions and recommendations were developed. This appreciation includes support for its strengths and where the authors have probed and perhaps exceeded the reasonable limitations of their data. In that regard these recommendations will include all of those presented by authors of individual chapters as well as some that have come out of this TR. However it must be kept in mind that these are only recommendations and their adoption is strictly a matter of individual national preference. Because of the uncertainties contained within this TR, the first general recommendation has the highest priority.

15.2 GENERAL RECOMMENDATIONS

The first general recommendation is to **continue research** in this important area of occupational medicine. Perhaps someday the perfect prospective longitudinal study will be conducted that will involve several thousand fighter pilots with G and age-sex matched controls, beginning with their careers of flying high performance aircraft and continuing until their death. Of course this study would be extremely costly, the logistics most complex (especially if international in

scope) and would take several decades to complete. Yet Sweden (Chapter 11) and Finland (42) have begun prospective longitudinal studies on their own. These studies although limited in numbers of subjects, are planned to be continued for several decades.

On the other hand, an extensive cross-sectional study would be extremely valuable in developing useful data and could be completed fairly rapidly and with less logistical support and cost than the longitudinal study. Incidentally, AR 317 contains a cross-sectional study proposal that was never conducted. Its design has merit. However until the definitive study has been completed, additional data will come to us fragmented, sometimes scientifically tainted, but still information that must be reviewed, analyzed and integrated into the existing knowledge base. Generally the TW has used that approach in this TR and perhaps this TW should be continued by RTO.

It is essential that **more information** be made available on this subject of cervical spinal degeneration. The information within this TR is not conclusive on this subject. This TW on cervical spinal injury has documented, reviewed, and analyzed several case reports and recent (sometimes ongoing) control studies on this subject. Yet it is still not entirely clear to what extent or precisely how increased sustained G affects the natural aging processes of the cervical spine. A simple model has been developed herein that must be validated and expanded. Certainly this model is only a start.

The AGARD Advisory Report 317, "The Musculoskeletal and Vestibular Effects of Long Term Repeated Exposure to Sustained High G" recommended the establishment of this TW instead of a specific multinational study of pilots (3). That recommendation was defended in AR 317 listing several reasons. Advisory Report 317 also recommended another symposium on this topic at the end of this decade. **It is now recommended that a RTO Symposium be conducted on this subject, but not for another 5-10**

years. The reason for postponing it several years is because the TW has been diligent in its role as gatekeeper on this subject. The information contained within this AR is complete, current and only one major study is ongoing (42). Perhaps this TR will stimulate additional well-focused research efforts in this area. Such studies will take several years to complete, so that reports on their data would not be available until the close of the next decade. On the other hand, an RTO Symposium 'Operational Issues of Aging Crew Members' scheduled for 1999 in France has some relevance to this problem of cervical spinal degeneration.

In conducting **additional studies** on this subject, it is recommended that other sections of the spine be included. This TW focused on the cervical spine because that is where most acute injuries occur in fighter pilots. Also biomechanical models indicate that the cervical spine is at greatest risk during exposure to the ACM environment. Therefore, this section of the spine also must be most vulnerable to degenerative changes. Indeed, most reports/studies on this subject include only the cervical spine, so most of our information is on that region of the spine. On the other hand, the lumbar region of the spine is an area that has been identified as potentially at risk from repeated sustained G exposures by several of the studies reported herein. **It seems prudent therefore that future studies, directed towards spinal injury from sustained G exposures in fighter pilots, include the lumbar spine.**

The combined effects of the sustained G environment and the **aging process of the cervical spine** on pilots should be investigated. This TR theorizes that this degeneration process is accelerated in some pilots during their second and third decade of life from repeated exposures to sustained G. Since much of this aging process involves spondylosis that is considered a mechanism to strengthen vertebrae, its value in supporting the spine as pilots age must be determined. If the spine of the fighter pilot is stronger with spondylosis, then its aging process should slow down once the pilot stops being exposed to sustained G. In the non-flying population, the aging process of the cervical spine will continue at a more rapid (natural) rate. Thus later in life (approximately 60 yrs of age), the cervical spines of the majority of fighter pilots will not have significantly greater degrees of degeneration compared with non-flying controls. In support of stronger vertebrae in flying population, Stupakov et al (Chapter 8) reported an increased mineral density of 16% in the vertebrae of fighter pilots.

Additional studies will be conducted by various nations concerned with this potential operational problem. Before these studies begin, a **standardized nomenclature** should be developed to describe spinal injuries and degeneration (60, 102). In addition, **an international database should be initiated.**

Biomechanical models that determine cervical injury thresholds from repeated sustained G exposures should be further developed. These models should predict the probabilities of acute neck soft and hard tissue injuries as well as the development of degenerative lesions of the spine. Impact models that accurately predict spinal injuries have been developed, but these are not appropriate for sustained G exposures (see figure 12-1). These sustained G models will also be useful in better determining weight and balance specification for head-mounted equipment for aircrews.

15.3 SPECIFIC RECOMMENDATIONS

15.3.1 Treatment of Neck Injuries

Acute soft tissue injuries of pilots from exposures to increased sustained G should be considered as serious injuries requiring accurate diagnoses and aggressive forms of treatment for two important reasons:

1. Subclinical overload injuries which decrease natural cervical spine protection can lead to overt injuries that will require more time to heal, seriously impact mission readiness, and perhaps long-term well-being.
2. Exposure to high-sustained G with soft tissue injuries of the neck can potentially increase significantly serious acute injuries of the spine and perhaps accelerate the process of degeneration.

Treatment of these acute injuries should include a rehabilitation program that stresses increased muscle strength to prevent its reoccurrence and provide greater support for the cervical spine.

Flight surgeons should be made aware of the importance of neck injuries and the potential for more serious injuries that could lead to chronic conditions. Obviously, pilots should be made aware of the increase in risk of spinal injury while flying with sore necks.

There is an opportunity for flight surgeons to investigate new methods for prevention and treatment of neck

injuries. Neck soreness immediately after flight can be treated with supine rest to alleviate the weight of the head on the neck and to restore fluid loss to the disks. Neck muscle massages, saunas and cervical spinal 'manipulations' might be tried. These physical-based treatments for athletics are routine following strenuous sporting events (e.g., American football, baseball, hockey and basketball).

15.3.2 Prevention of Neck Injuries

The selection process for pilots should include some form of spinal diagnostic imaging to check for spinal abnormalities. A selection process has been developed and used for many years by the Royal Netherlands Air Force (RNLAf). Between November 1982 and January 1985, they rejected 20% of candidate student pilots because of spinal disorders found with radiography (124). The RNLAf found that clinical examinations without spinal radiography were not an adequate screening system (125). Unfortunately the value (cost benefit) of including the spine in the pilot selection process as it relates to sustained-G spinal injuries and degeneration has not been determined.

Physical conditioning programs that are known to increase G-level and G-duration tolerances should continue to be encouraged and supported by the operational communities of all nations (26). These training programs should include a well-designed neck muscle-strengthening regimen (16). In support of this recommendation, more research should be conducted on physical training methods for necks of fighter pilots. These studies should include **improved training regimens** that are more rapid and effective in increasing neck strength that is functionally balanced for the fighter pilot. A study that determines the agonist and antagonist muscles of the neck used by pilots during ACM should be determined in order to develop resistance training regimens that provide balanced muscle strength in support of the cervical spine. Another study should consider the **benefits of these physical training programs** in preventing acute neck injuries and spinal degeneration.

Since individual pilots cannot predict their level of risk, they should **use all known preventative measures**. These include **preflight warm-up exercises** of the neck and **developing strength in neck muscles**, particularly those that are used in the ACM environment. Also **movements of the head**, especially rotation and extension, during exposures to increased sustained G

should be accomplished minimally, with care and caution.

Pilots should also develop good personal health-related habits such as maintaining proper body weight, healthy diet, and erect posture.

Improved design for life-support equipment and protective systems that are located on the head that are lighter weight and reduce the load moment would significantly reduce the risk of acute neck injury. Aircraft seats for fighter pilots should be developed with sound ergonomics in support of the neck and head.

Mechanical neck-mounted equipment has been designed that automatically provides structural support for the neck during increased G exposures or during rapid involuntary movements of the head. These designs should be reconsidered, prototyped, and perhaps even flight tested for their ability to prevent acute neck injuries, allow for sufficient head movement to perform operational tasks, and of course be evaluated for pilot acceptance.

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Russell R. Burton, Chairperson, Technology Watch

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14. Abstract Published articles and reports on current studies by several nations on cervical neck injury, spinal degeneration and related topics are reviewed and analyzed in detail in the first 11 chapters. In Chapter 12 the biomechanics of the cervical spine and predictive models on cervical injury from sustained G exposures are presented. Meta-analysis of 8 control-studies on the direct effects of sustained G exposures on cervical degeneration was performed and presented in Chapter 13. The statistical probability of a causal relationship was determined to be $P < 0.001$. In Chapter 14, this information was summarized and further developed into a model on the relationship between aging and sustained G exposures on cervical spinal degeneration. In this model, cervical spinal degeneration occurs with repeated exposures to sustained G and with aging. However because of the continuous and pervasive effects of aging, the pilot population and non-G exposed population (controls) are predicted to have the same levels of cervical degeneration later in life. Recommendations presented in the last chapter include the need for more research on this topic, the development of standardized nomenclature and databases, and specific considerations on the prevention and treatment of acute neck injuries. (138 references)					



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